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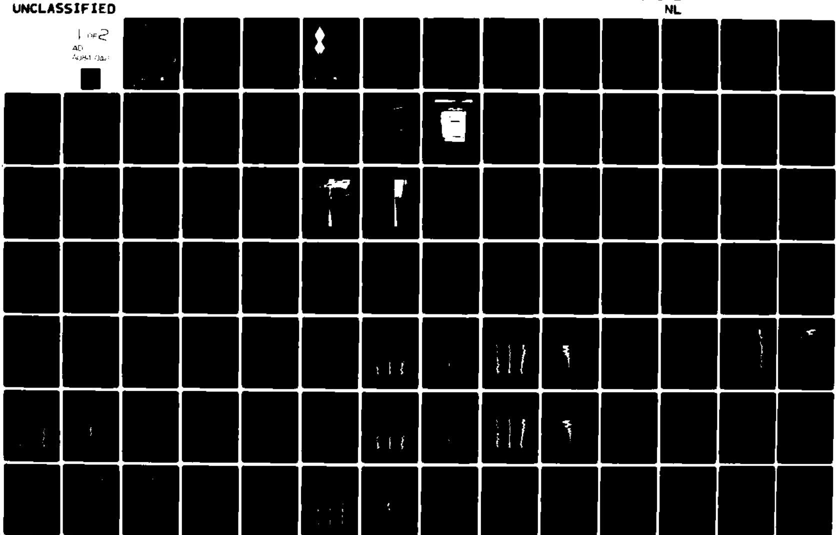

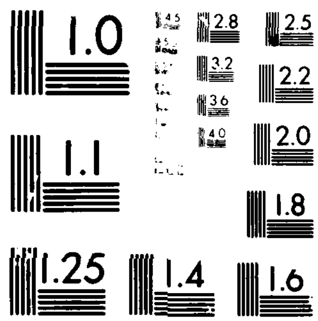

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FEASIBILITY STUDY OF TRISCAN LANDING SYSTEM

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Prepared for:

NAVAL ELECTRONICS LABORATORY CENTER
San Diego, California 92152

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This report describes the AIL CO-SCAN SYSTEM (commercial version of the Navy's AN/SPN-41) configured in an arrangement to perform triangulation measurements to obtain the three dimensional position coordinates of a receiver; and the results of a field test program that evaluated its performance accuracies.

FEASIBILITY STUDY OF TRISCAN LANDING SYSTEM

Final Report
October 1977

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1.0 INTRODUCTION

The Navy Vertical Takeoff and Landing Project (NAVTOLAND) has been established to improve the hover, approach and landing capabilities of Navy and Marine Corps V/STOL aircraft. These aircraft may be required to operate from aviation facilities ships (non-aviation ships), small aviation ships (such as LPH, LHA, VSS) and Marine Corps tactical sites. Common problems in the aircraft missions include operations under severe weather, day and night, often requiring the landing in a confined area. The NAVTOLAND program will correlate and investigate the development of all systems and techniques which are involved in enabling the pilot to fly V/STOL Aircraft onto Navy Ships and Marine Corps tactical sites.

Guidance sensors have been identified as being critical to the NAVTOLAND program. A guidance sensor is required to determine the three dimensional position of the V/STOL relative to the landing zone. In low visibility operations, sensors are needed to enable the pilot to locate the ship and initiate his approach; and if the landing site has zero ceiling, the guidance sensors will be required for the pilot to make the final approach. This points out the stringent accuracy requirements that must be achieved for the aircraft operations to be conducted safely. In particular, three dimensional accuracies for position of ± 1 foot and range rate of 1 foot per second and an update rate of 10 times per second are required. Table 1-1 lists the target requirements that have been established for the NAVTOLAND guidance sensor.[1]

This report describes the AIL CO-SCAN system (commercial version of the Navy's AN/SPN-41) configured in an arrangement to perform triangulation measurements to obtain the three dimensional position coordinates of a receiver; and the results of a field test program that evaluated its performance accuracies.

[1] NAVTOLAND Program Plan, ADPO-11, Naval Air Systems Command, September 1976, Parayraph 2.4.2.

The test range depicted in Figure 1-1 utilized a mechanized 40 foot mast with a modified AN/ARA-63 receiver moving on a range calibrated rail, toward TRISCAN transmitting stations in an induced multipath environment. About 1,000 test runs using this device, instrumented with recorders, were performed under various multipath conditions. Tests were first performed at various and varying angles from 900' to 15' from the transmitters, with a normal runway environment. The tests were then repeated with a 48' X 100' reflector on the runway surface in front of the transmitters to simulate deck reflections. Tests were again repeated with several combinations of 8' X 8' vertical reflectors placed behind the transmitter station and off to one side of the approach path. Finally, a 4' X 8' vertical reflector was added behind the receiver to simulate double bounce multipath conditions. High speed (30 mile per hour) tests were also performed in this environment. When areas of multipath were encountered, the region was probed to record the magnitude of the multipath. The tests were witnessed by personnel from NELC and all of the raw data recorded was supplied to NELC.

These tests have provided data that have established:

1. Basic system position accuracies

2. RF multipath effects

3. Range rate accuracies

The results indicate that TRISCAN has position accuracies of ± 1 foot at ranges under 100 feet with velocity accuracies better than 1 foot per second out to 300 feet ranges. At 600 feet range, the errors are 33 feet (bias included) in range and 3.14 feet per second for range rate; and the range error increases to 55 feet (bias included) at 800 feet range. At these larger ranges, a significant portion of the error is due to multipath effects in addition to the geometric dilution of precision caused by converting angular data to rectangular position coordinates.

The performance capabilities of TRISCAN that have been demonstrated by this test program are shown in Table 1-1. Although not expressly demonstrated in this program, TRISCAN characteristics that have been shown by related equipment are indicated.

In addition to the TRISCAN system and tests, critical areas relevant to guidance sensor requirements are analyzed in this report. These are signal stabilization (ships motion compensation), data link requirements, and waveoff capabilities.

TABLE 1-1

GUIDANCE SENSOR PARAMETER	NAVTOLAND GUIDANCE SENSOR TARGET REQUIREMENTS	TRISCAN FIELD TEST RESULTS		PRIOR SYSTEM EXPERIENCE
ACCURACY	1 foot or better in position Filter Time Constants 0.57 secs Range 0.28 secs Crosstrack 0.28 secs Height	RANGE	Better than 1 ft within a distance of 100 feet	
		CROSSTRACK	Better than 1 ft within a distance of 500 feet	
		HEIGHT	Better than 1 ft within a distance of 500 feet and 3° elevation angle	
	1 ft/sec or better in velocity Filter Time Constants 1.85 secs Range 0.93 secs Crosstrack 0.93 secs Height	RANGE	Better than 1 ft/sec within a distance of 300 feet	
		CROSSTRACK	Better than 1 ft/sec within a distance of 500 feet	
		HEIGHT	Better than 1 ft/sec within a distance of 500 feet and 3° elevation angle	
COVERAGE	±40° azimuth coverage at outer range	±17°		Requires mechanical change in scan cycle. A-SCAN had ±60° azimuth coverage
	2° to 20° elevation at outer range	2° to 18°		Requires mechanical change in scan cycle. NASA Space Shuttle MSBLS has 1.3° to 30° elevation coverage
	AZ/EL coverage in-close sufficient for guidance to touchdown	YES		
	Minimum operating range = touchdown point	YES		

TABLE 1-1. (CONTINUED)

GUIDANCE SENSOR PARAMETER	NAVTOLAND GUIDANCE SENSOR TARGET REQUIREMENTS	TRISCAN FIELD TEST RESULTS	PRIOR SYSTEM EXPERIENCE
COVERAGE (CONT'D.)	Maximum operating range = 3 - 5 nautical miles	Not applicable to this test program	Can provide azimuth and elevation guidance to 10 miles similar to AN/SPN-41 guidance
	Waveoff coverage desired	Not applicable to this test program	
UPDATE RATE	10 per second minimum	4 per second (standard COSCAN cycle rate	Can be provided. Flarescan had a 10 sample/sec update rate
VISIBILITY MINIMUMS	50 to 700 feet	Not applicable to this test program	
SEA STATE	Up to Sea State 5	Not applicable to this test program	
RAIN	Heavy rain up to 16 mm/hr	Not applicable to this test program	AN/SPN-41 has demonstrated operation under these conditions
SHIPBOARD LANDING DECK SIZE	40' X 40' minimum	Not applicable to this test program	
DATA QUALITY	Sufficient for piloted and automatic landings	Not applicable to this test program	Auto landings and touchdowns have been demonstrated (Boeing Report D180-18692-8 Compass Cope Program RPV Autoland Demonstration)

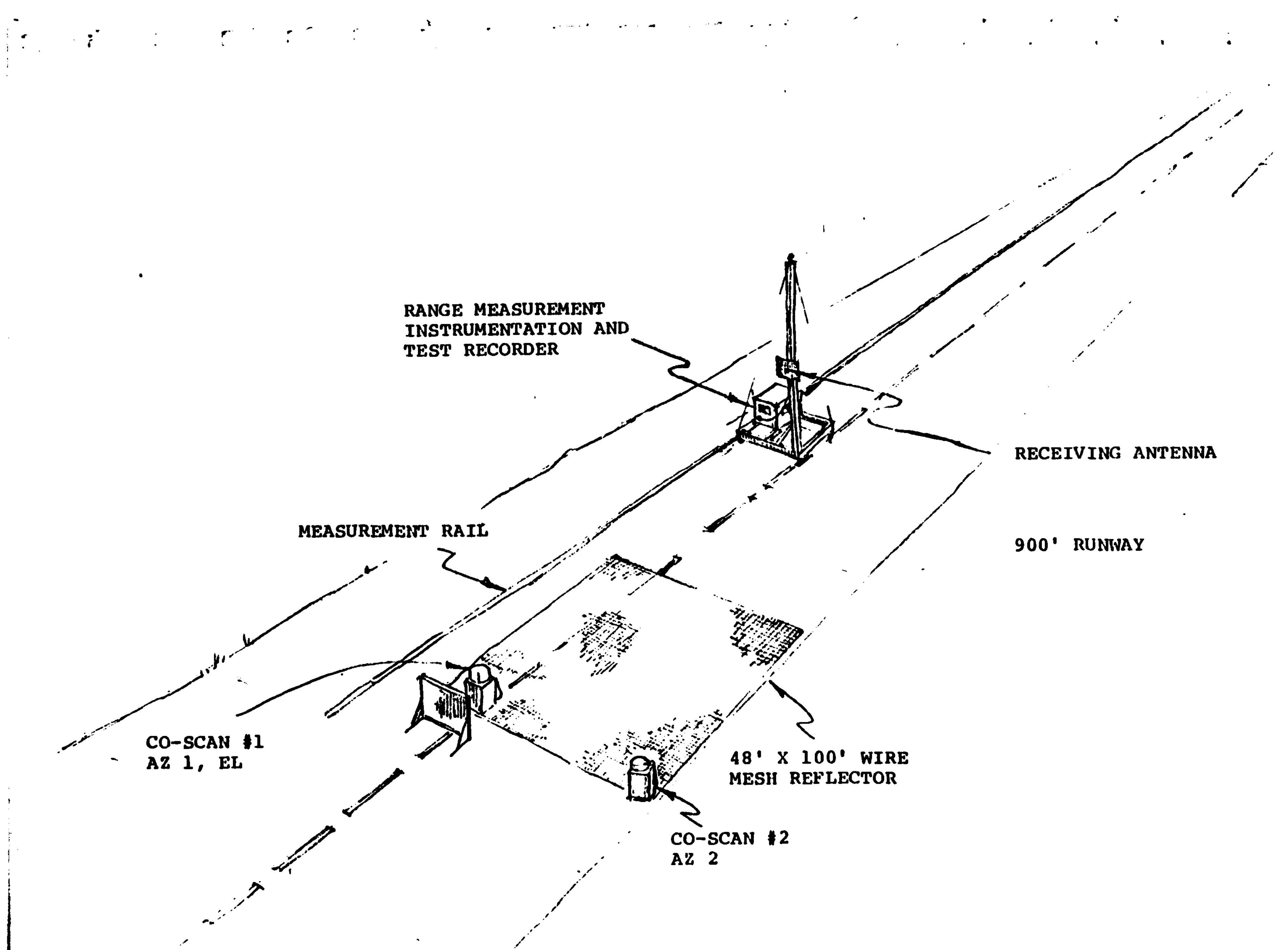


FIGURE 1-1. TRISCAN/NAVTOLAND TEST CONFIGURATION

2.0 TRISCAN SYSTEM DESCRIPTION

2.1 SYSTEM FUNCTION

TRISCAN is a microwave scanning beam landing system that provides a course (Azimuth 1), a range (Azimuth 2) and a height (Elevation) by radiating from two locations along the edge of a ships landing zone. The proposed arrangement is to incorporate Azimuth 1 and Elevation antenna elements at one location and Azimuth 2 at the second location. The antennas, which rotate at a high rate, are small and are all phase locked so that one antenna radiates while the other two are passing through their inactive portion of rotation. Thus, a single set of electronics can serve for both azimuths and the elevation functions. As the beams scan, they radiate a continuous train of pulse pairs, a code which: (1) identifies the transmission as azimuth 1, azimuth 2 or elevation information, and (2) gives the instantaneous pointing angle of the beam.

The pulse code structure is shown in Figure 2-1. Note that the angle value is represented by the interval between second pulses of any two adjacent pairs. The relationship is simply:

$$\text{Interval (microseconds)} = 2 \times \text{angle (degrees)} + 60.$$

Thus, as shown, zero degrees in either azimuth or elevation is represented by an intrapair spacing of 60 microseconds and this value increases smoothly, for instance it is 100 microseconds at 20 degrees. An important feature of this code is that it is continuous. The interval being broadcast is updated as the antenna moves so that it always represents the pointing angle of the beam on an instantaneous basis.

Transmissions are identified by the spacing of the pulses of any pair; elevation transmissions consist of 12 microsecond pairs, while azimuth 1 uses 10 or 14 microsecond pairs and azimuth 2 uses 11 or 15 microseconds. Two separate pair spacings are used for each azimuth to provide effective sign information on azimuth angle data, allowing the zero degree point to be placed at the center of scan.

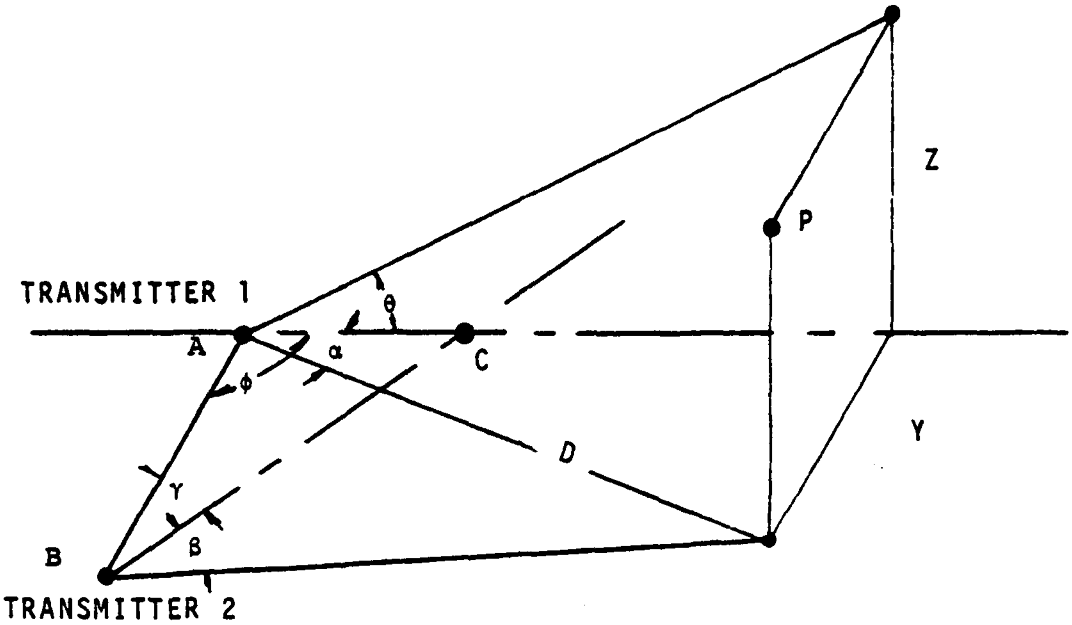
The system, which operates in the 15.4 to 15.7 GHz Ku-Band, has been divided into 10 RF channels. Doubling of the number of system channels is achieved by reusing the same RF channels with a 1 microsecond increase in all ident spacings. Geared to each antenna is an angle data pickoff (ADP), an optical shaft encoder that generates electrical signals representing the antenna position. This data is converted into the required pulse code in the digital unit, which produces modulating signals for the transmitter. RF flows from the transmitter to a waveguide switch coupled into the antenna drive mechanism. This switch provides a waveguide path between each antenna and the transmitter during the appropriate portion of the transmission cycle.

In the air, the receiver portion of the system sees a burst of pulse pairs, sequentially, representing azimuth 1, azimuth 2 and elevation. Conventional receiver techniques produce video pulses whose function is determined on the basis of the intrapair identity spacing, and an AGC voltage for each function independently. By averaging the intrapair (pointing angle) spacings for each functions, the receiver measures a precise angle that is used in the geometric calculations.

2.2 SYSTEM GEOMETRY

As with all aircraft landing situations, the basic questions are; where is the aircraft in relation to the touchdown area? For a complete solution, the X, Y, and Z coordinates of the aircraft with relation to the touchdown must be known. The aircraft receiver decodes the three angles and by knowing the baseline, (which is sent to the aircraft via a data link) a microprocessor can compute the relative X, Y, and Z coordinates. From this, data such as range rate can be readily computed.

The TRISCAN testing described in this report was done with two azimuth transmitters and one elevation transmitter. The geometry of the testing is shown on the following page.



Point C is where the zero degree azimuth line from transmitter #2 crosses the zero degree azimuth line of transmitter #1. Point C has X, Y, and Z coordinates of (0, 0, 0). During the setup of the transmitters, the following values must be determined $\overline{AB}$, $\overline{AC}$, $\angle BAC$ and $\angle ABC$.

Now, if the X-axis is chosen as the zero degree azimuth of transmitter #1, the X, Y, and Z coordinates of Point P can be determined from the following equations:

1. $$D = \frac{c \sin (\beta + \gamma)}{\sin (-\alpha + \beta + \gamma + \phi)}$$

2. $x = D \cos \alpha - d$

3. $y = D \sin \alpha$

4. $z = D \cos \alpha \tan \theta$

5. $R = \sqrt{x^2 + y^2 + z^2}$

where:

$c = \overline{AB}$

$d = \overline{AC}$

α = received azimuth angle from transmitter #1

β = received azimuth angle from transmitter #2

$\gamma = \angle ABC$

$\phi = \angle BAC$

θ = received elevation angle

R = range from Point P to (0,0,0)

It must be remembered that azimuth angle #1 is positive in the fly-right region and negative in the fly-left region. Azimuth angle #2 is reversed, i.e., positive in the fly-left region and negative in the fly-right region.

2.3 EXPERIMENTAL TEST EQUIPMENT

In order to implement the tests required to prove the TRISCAN concept, two CO-SCAN units were specially modified. CO-SCAN, see Figure 2-2, is AIL's commercial microwave landing system that uses the same signal format as TRISCAN. In addition, a specially modified AN/ARA-63 was employed as the receiver for these tests.

The CO-SCAN ground set scans only ±20° in azimuth and from 0 to 20° in elevation (Figure 2-1). Therefore, the regions of coverage are considerably less

than that proposed for TRISCAN. To make up for this deficiency, the bore siting of the CO-SCAN's was changed in stages to cover the region of interest. One CO-SCAN provided azimuth 1 and elevation coverage, and the other had its elevation scanner disconnected so that only azimuth 2 was transmitted from it.

Because the standard CO-SCAN is not designed for wide angle coverage, two test positions for azimuth station #2 were necessary to fully test the TRISCAN configuration. The total range out to 900' was separated into sections - a short range sector 16' to 60' and a long range sector 52' to 900'. Accordingly, the cross over range, Point C, was 33.2' for the short range sector and 106.4' for the long range sector.

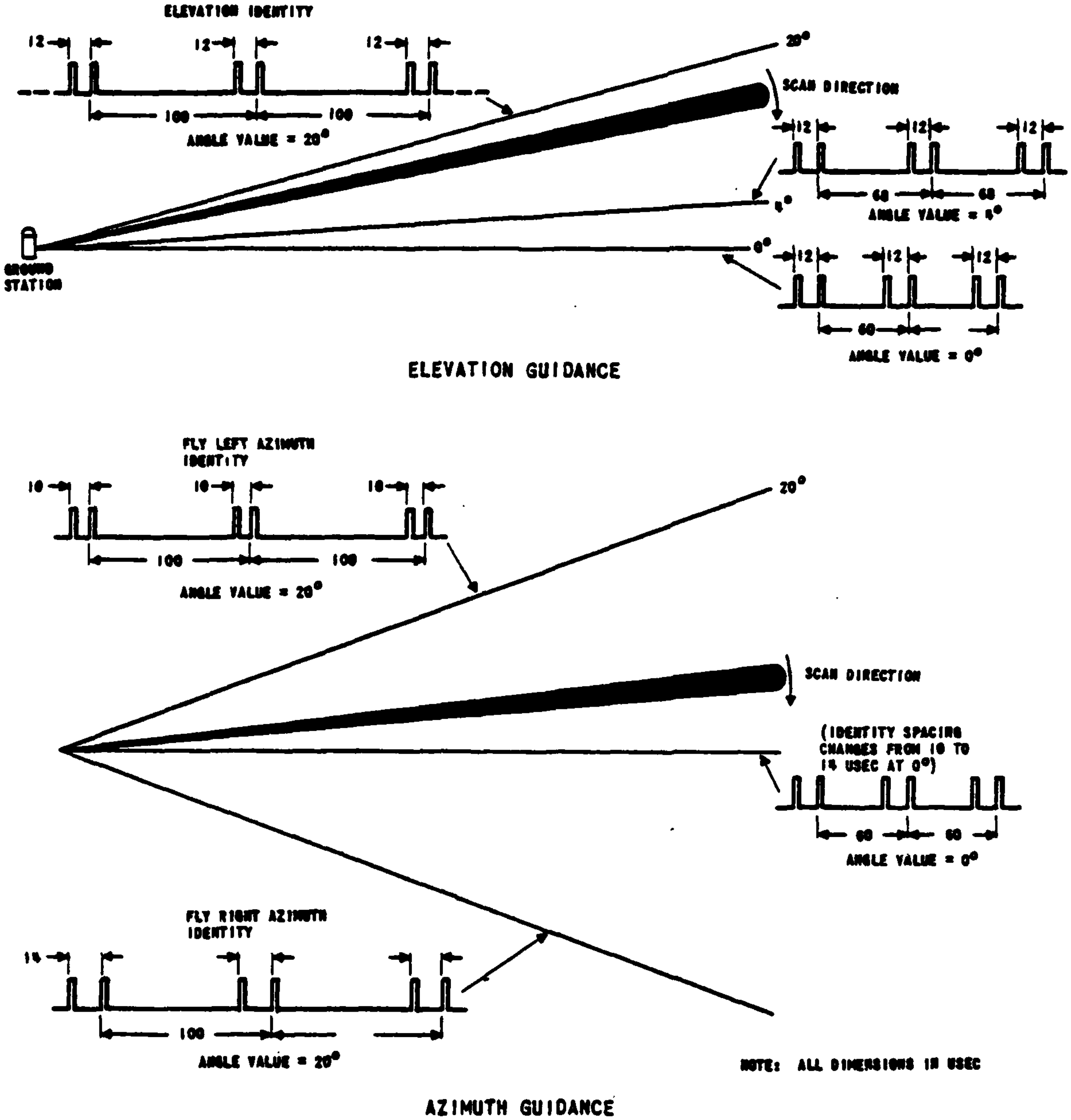
Receiver modification included bringing out appropriate digital signals from the receiver decoders that could be used to feed the data recording system which was to provide a continuous record of the system performance during the accuracy tests.

Figure 2-3 shows the general block diagram of the TRISCAN system. Since only one common RF front end is used for both decoders, the two ground stations had to be synchronized so that only one transmitting antenna was energized at any one time. This was done digitally by comparing the shaft encoder (ADP) positions of the two ground stations and then introducing a speed correction, if necessary, to the DC motor driving the No. 2 azimuth antenna. In this way, the three transmissions were spaced approximately 70ms apart with the azimuth 2 scan occurring between the azimuth 1 and elevation scans.

For the tests, both stations were transmitting at the same RF frequency, but with different ident pulse spacings, allowing one decoder to receive the transmission of one ground station while rejecting the transmission of the other ground station and vice versa. Each decoder was tied into a control unit which determined the channel to be received by that particular decoder. The AGC signals from the two decoders were routed through a multiplex circuit which chose the stronger signal and sent it on to the RF front end.

The AN/ARA-63 receivers used for the TRISCAN tests normally have a proportional deflection area of ± 6 degrees for azimuth and ± 1.4 degrees for elevation. In order to utilize the full deflection range that these receivers are capable of ($\pm 20°$ for azimuth and $+20°$ elevation) minor changes to the maximum error limiter circuits in the decoders were made. Also, the glide slope reference signal, which normally is the manually selected glide slope angle, was hardwired to zero degrees, thus referencing all elevation angles to the horizon.

Extra output wires and connectors were added to the decoders in order to bring out raw digital signals that ordinarily were used in computing the cross pointer indication. These digital signals were fed to an AIL built recorder interface unit where they were processed to a format suitable for recording onto a DATUM Model 4000 cassette recorder. In this way, it was possible to automatically record the angular data associated with each separate azimuth and elevation antenna scan. A commercial 28VDC power supply was used to power the receivers.



3-58

FIGURE 2-1. PULSE CODE STRUCTURE

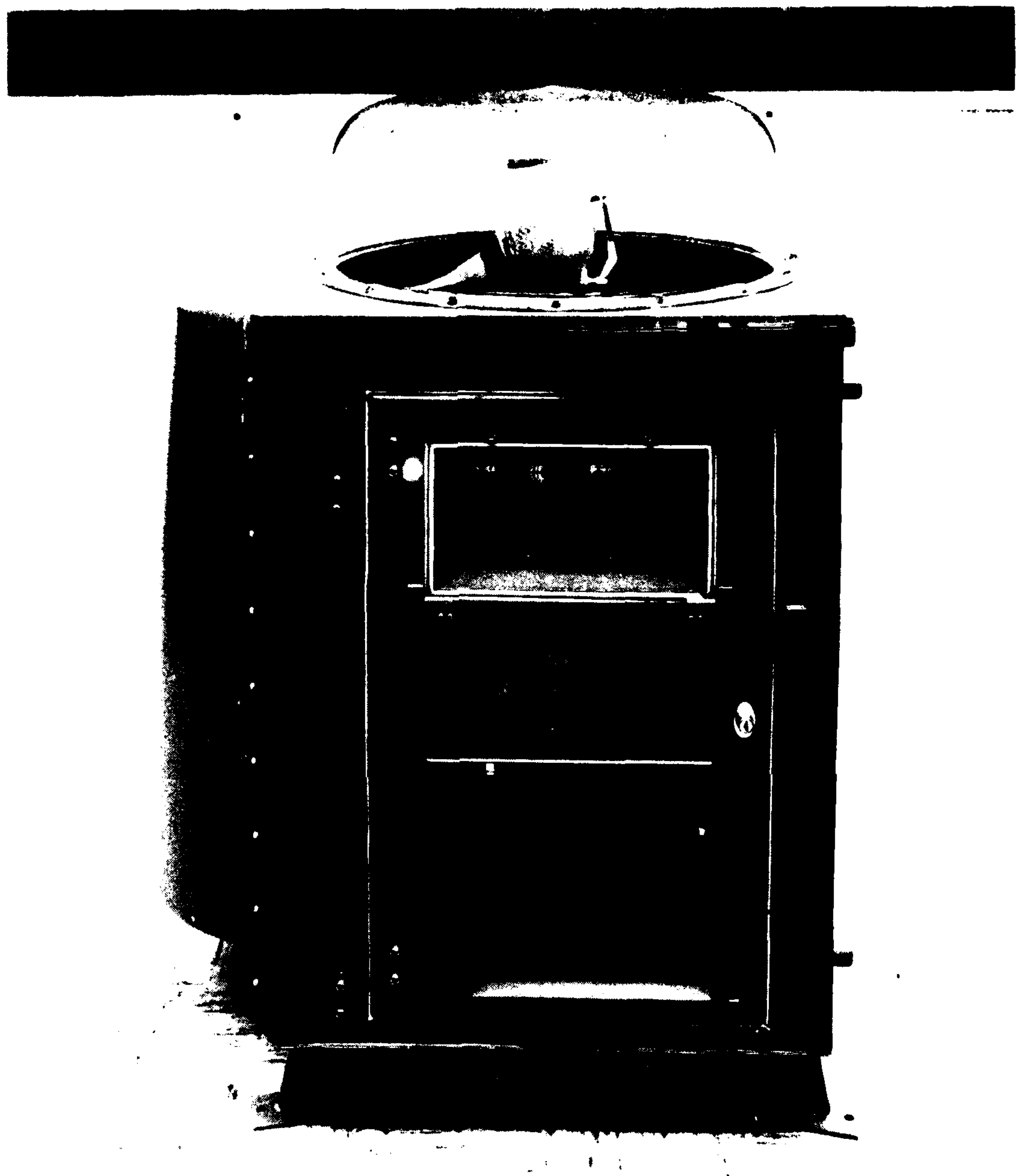


FIGURE 2-2. COSCAN

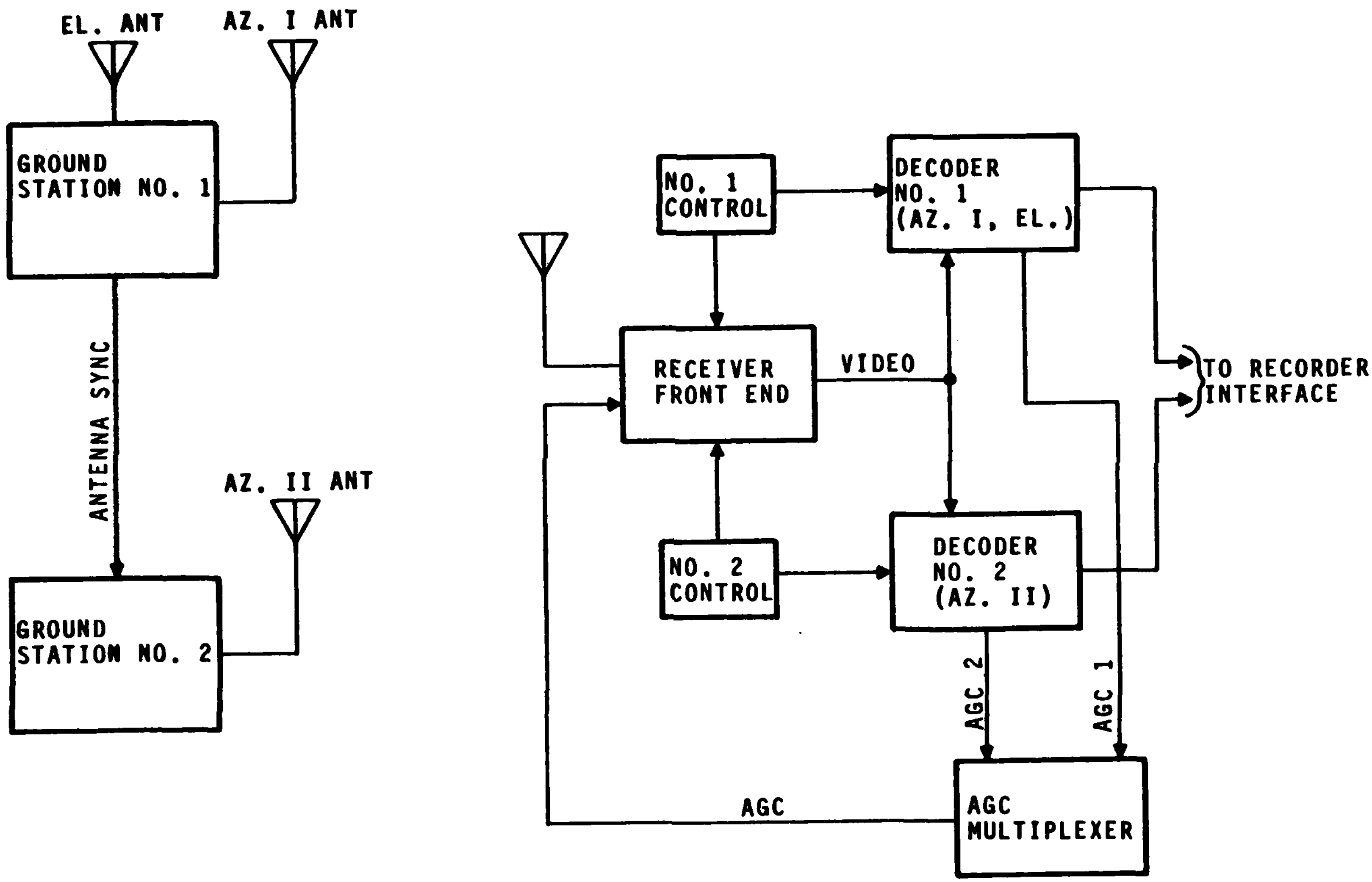


FIGURE 2-3. TRISCAN GENERAL BLOCK DIAGRAM

3.0 TEST PLAN

The purpose of the test program was to obtain data that would determine TRISCAN system performance capabilities. Specifically, the field tests were designed to provide data that would establish:

1. Basic system positioning accuracy
2. RF Multipath Effects
3. Range Rate Accuracy

The TRISCAN field test installation measured the azimuth angles of the receiver with respect to the two ground stations and the elevation angle with respect to one station. The measurements were recorded on magnetic tape for later playback into a calculator. The calculator provided a statistical analysis of azimuth #1 angle, azimuth #2 angle, elevation angle, computed receiving antenna position and range rate. Concurrently, the receiving antenna's actual position, range and height were also recorded to provide the reference data. The angles and related data were updated at the 4 Hz scan rate of the CO-SCAN.

3.1 SYSTEM AND SITE INSTALLATION

The simplified block diagram of the general approach and field test instrumentation setup is shown in Figure 3-1 and the field layout is shown in Figure 3-2. The system transmitters are the standard CO-SCAN ground stations with Station #2's elevation transmission disabled. A standard synchronizing signal is used to ensure the correct synchronization (with no overlap) of the three angle data transmissions per cycle. The modified ARA-63 receivers are fed from a single receiving antenna and RF unit. Receiver outputs are the angle data in binary code and the analog AGC voltages. The interface processes the AGC signals to route the proper AGC voltage to the RF head, depending on the specific guidance signals being received.

The other interface inputs are the true position data of the receiving antenna. These are generated by 14-bit encoders that provide accuracies considerably better than 1 inch in range and 0.08 inches in elevation. A self contained clock generator provides the accurate timing reference marks. This supplies the correlation information required for data reduction and analysis of system performance. The interface formats the input data and feeds the magnetic tape recorder directly.

The interface also has a "quick look" capability for real time verification of system operation. The 3 received parameters, Azimuth #1, Azimuth #2 and Elevation are displayed continuously by a decimal readout. Therefore, as testing proceeded, the operator verified that all system components, including test system instrumentation, were working properly and valid data was being recorded.

Initial testing was performed under clean site conditions, e.g., no reflecting objects. Afterwards, combinations of reflecting screens were used to simulate structures. The sizes and locations of these reflectors are shown in Figure 3-2.

A photograph of the test range seen from behind the carriage looking toward the transmitting stations is shown in Figure 3-3. The photo was taken with the vertical reflecting screens and ground screen in place. The view of the test range looking towards the carriage is shown in Figure 3-4.

3.2 MEASUREMENTS

The conducted tests were classified into 3 major groups:

1. Static
2. Dynamic (slow velocity)
3. High Speed Truck Tests

The initial static tests utilized station #1 (both azimuth and elevation) to establish basic system

capabilities. Operation at several azimuth angles were checked. Since the carriage is restricted to straight line motion down the taxiway, the ground station was turned around its axis to provide the desired azimuth angle as seen by the receiver. Then the two station's TRISCAN configuration was run to analyze its static performance characteristics. This provided data under optimum conditions - no receiver motion.

The initial tests were made without reflecting screens to provide a performance baseline. Subsequently, tests were repeated with the reflecting screens to determine the effects of the multipath conditions.

The test plan called for the reflecting screens behind the transmitter and receiver to be tilted; first 10° and secondly 20°, to set up double bounce multipath condition at a point close-in. Exhaustive testing witnessed by NELC personnel did not uncover multipath situations at the expected reflection points, although noticeable angular error perturbations were found at distances under 40 feet from the station.

Because tilted screens produce double bounce multipath effects over a limited range sector, it was difficult to get consistent results. Consequently, the screens were vertically oriented; for this multipath geometry is the most severe in the sense that the phenomena could occur over a larger sector and be observed longer; and again, the system was thoroughly examined for multipath conditions. As before, multipath conditions were seen within 40 feet distance and not at the longer ranges. Because the angle errors are at short ranges, the resultant linear errors are small. Although comparable to the accuracy requirements at short distances, they are not considered critical to TRISCAN performance. These tests and the analysis are discussed later in Section 4.3.

Static accuracy was checked from a minimum range of 20 feet to 900 feet maximum at elevations up to 39 feet. Dynamic accuracy was measured for constant elevation runs as well as along constant glide angle approaches. All dynamic measurements were repeated three times to verify repeatability of the data. Because much of the data is redundant, this report, for the sake of clarity, is limited to representative runs that quite clearly show performance capabilities of TRISCAN. Regardless, all raw data tapes of all runs have been supplied to the Navy.

For tests at the higher velocities, the receiving antenna was pole mounted at fixed heights on a truck with a fifth wheel assembly. Also, a photo electric detector unit was installed on the truck and retroreflective tape was placed at several ranges from the transmitting station. The fifth wheel contained an incremental encoder that generated pulses as a function of distance. The pulses fed a range counter that was preset as the truck passed over the first tape. The preset value was the distance of the tape from the station. The counter contents were recorded in the same manner described earlier for the carriage position encoders. Alignment along the zero degree azimuth of Station 1 was maintained by the vehicle driver who followed the taxiway centerline. At the test speeds, the lateral offsets were probably about ± 1 foot.

3.3 TEST PROGRAM SUMMARY

The intent of the test program was to thoroughly investigate TRISCAN performance under many different conditions of multipath, receiver speed and so forth, within the limits of the test facility. The test plan design followed a flexible format whereby certain prescribed tests initially run were followed by extemporaneous tests when warranted for further probing of system performance. The planned series of tests are briefly summarized below.

1. Single Station, Clean Site, Static Tests

   The static accuracy of the system was measured over the test range at various heights, ranges and at several azimuth angles.

2. TRISCAN, Clean Site,

   A. A repeat of 1 above except in the TRISCAN configuration (two stations transmitting).

   B. TRISCAN performance measured with the several types of receiver motion.

      (1) constant speed, constant elevation.

      (2) constant speed, fixed glide slope angle.

      (3) fixed position, vertical motion.

3. Single Station - Multipath

   A ground reflecting screen 48' X 100' in area was placed in front of the transmitting station prior to the following:

(1) repeat of 1 above.

(2) system performance was measured at constant speed and at two different elevations for several combinations of multipath configurations.

(a) ground screen only.

(b) ground screen and vertical reflector behind transmitter.

(c) double bounce tests with parallel reflectors behind receiver and transmitter tilted first 10°; and secondly 20°.

4. <u>TRISCAN Multipath</u>

A. Static accuracy with ground screen only.

B. Static accuracy with vertical reflectors behind transmitter and receiver with a third reflector 22 feet off and parallel to the centerline and 70 feet from station.

5. <u>TRISCAN Multipath Slow Dynamic</u>

TRISCAN performance was measured at constant speed and at two different elevations.

6. <u>TRISCAN Double Bounce Tests</u>

TRISCAN performance measured at two fixed elevations with parallel reflector screens behind transmitter and receiver, tilted, first 10° and second 20°.

7. TRISCAN, Multipath, Dynamic

With parallel vertical reflecting screens. Performance measured with several types of receiver motion.

(a) constant speed, constant elevation.

(b) constant speed, fixed glide slope angle.

(c) fixed position, vertical motion.

8. TRISCAN High Speed Truck Tests

Performance measured at two fixed elevations at relatively high speed approaches of 15 knots and 30 knots.

Although about 1,000 test runs were made in this test program, it is impractical and also unnecessary to include all the resultant data in this report.[1] Since 6 graphs on two sheets (3 angle errors and 3 position coordinate errors as a function of range) at a minimum are plotted for each approach, the report would have had over 1,000 pages of essentially redundant data due to, as noted earlier, the repeatability and consistency of results between runs. Therefore, since the intended application will have reflecting surfaces and is a multipath situation, and the final TRISCAN system configuration is with two operating stations, representative results typical of these conditions are presented herein.

---

1 Note that all raw data tapes have been supplied to the Navy technical officer.

In summary, the analysis of the test runs described later cover system performance under conditions of:

1. Static Accuracy.

2. Constant speed at various elevations.

3. Constant speed approaches at two different glide slope angles.

4. High Speed Truck runs at fixed elevations.

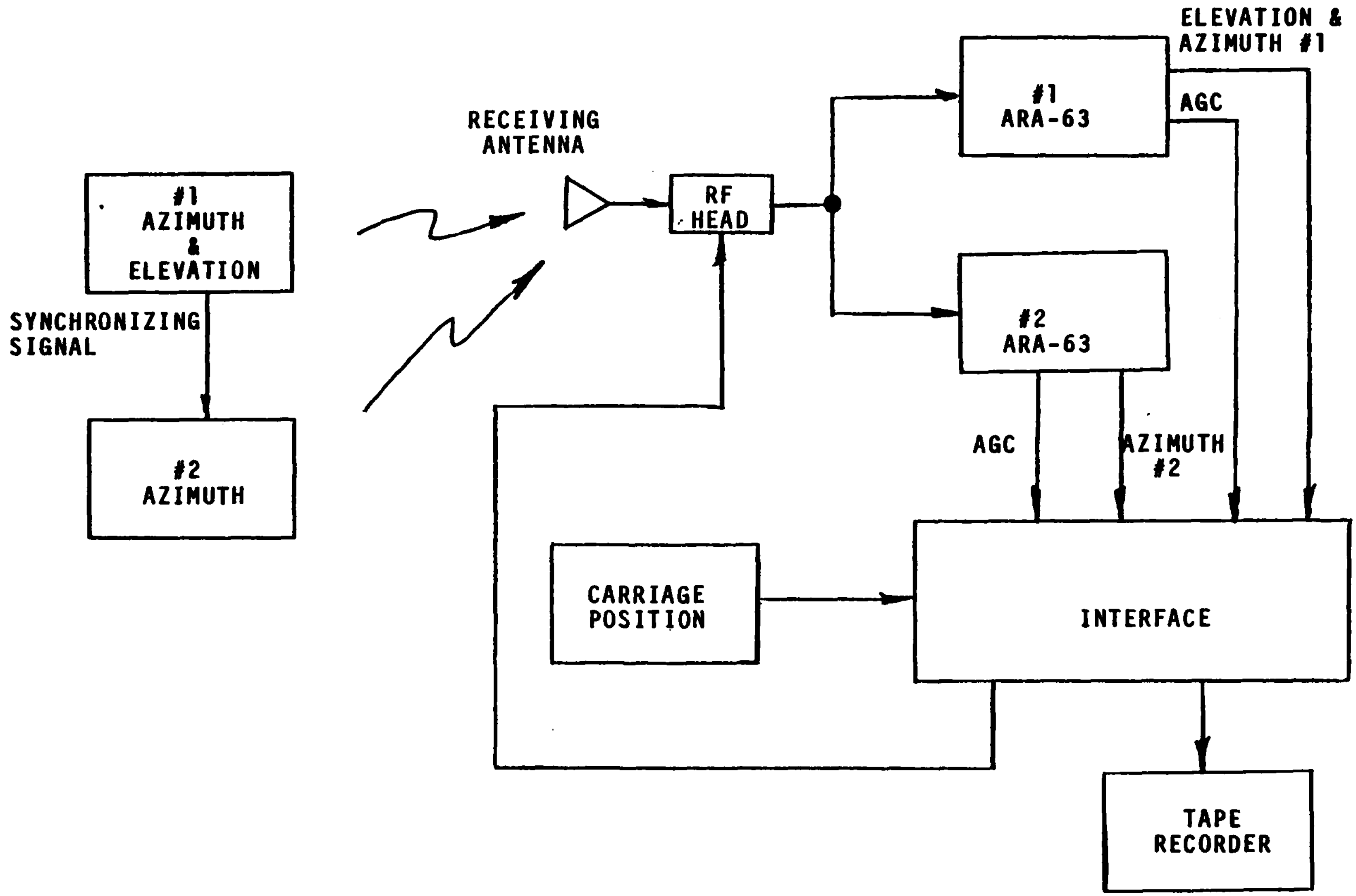


FIGURE 3-1. SIMPLIFIED BLOCK DIAGRAM FIELD TEST SETUP

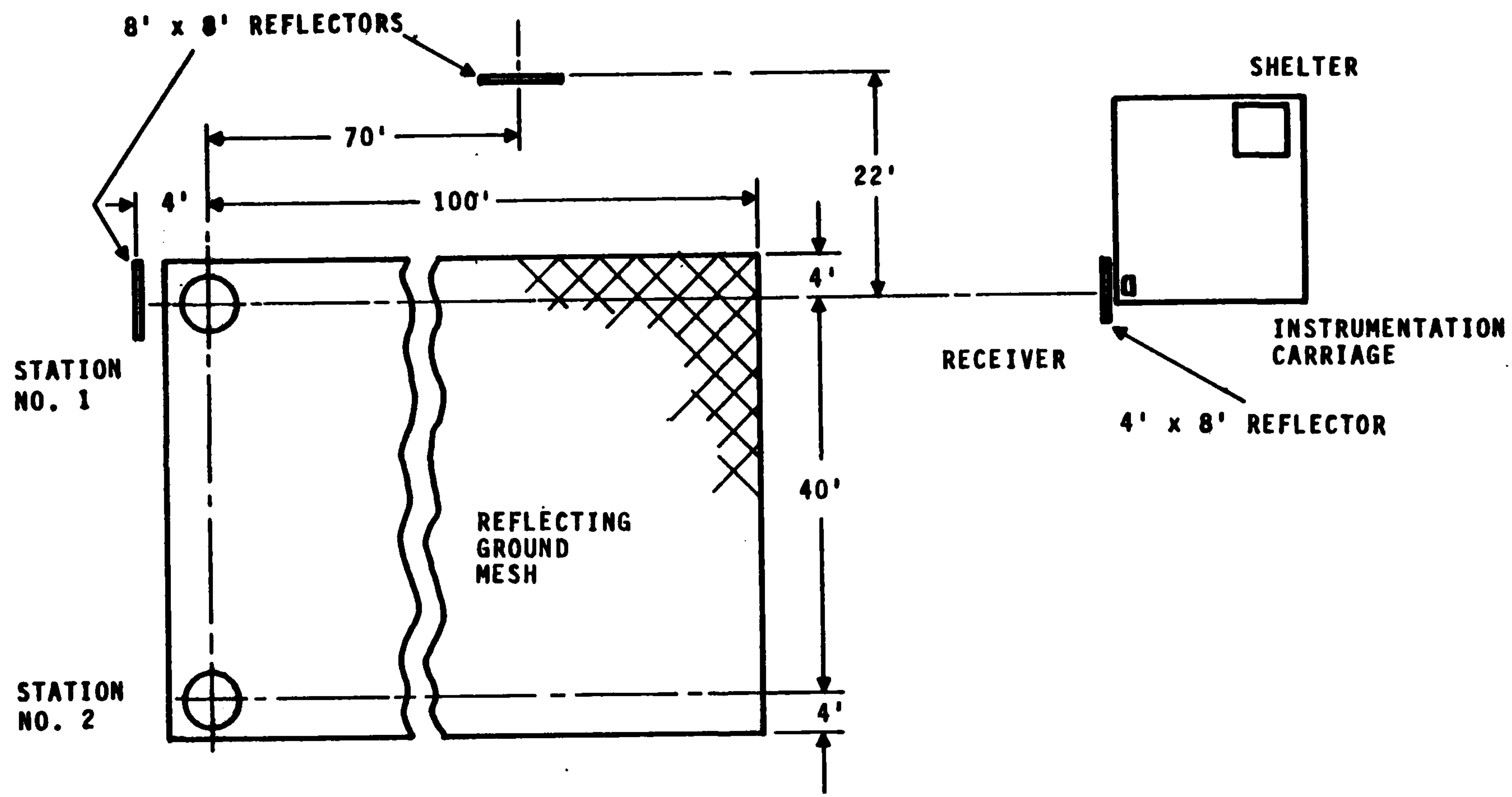


FIGURE 3-2. FIELD TEST LAYOUT

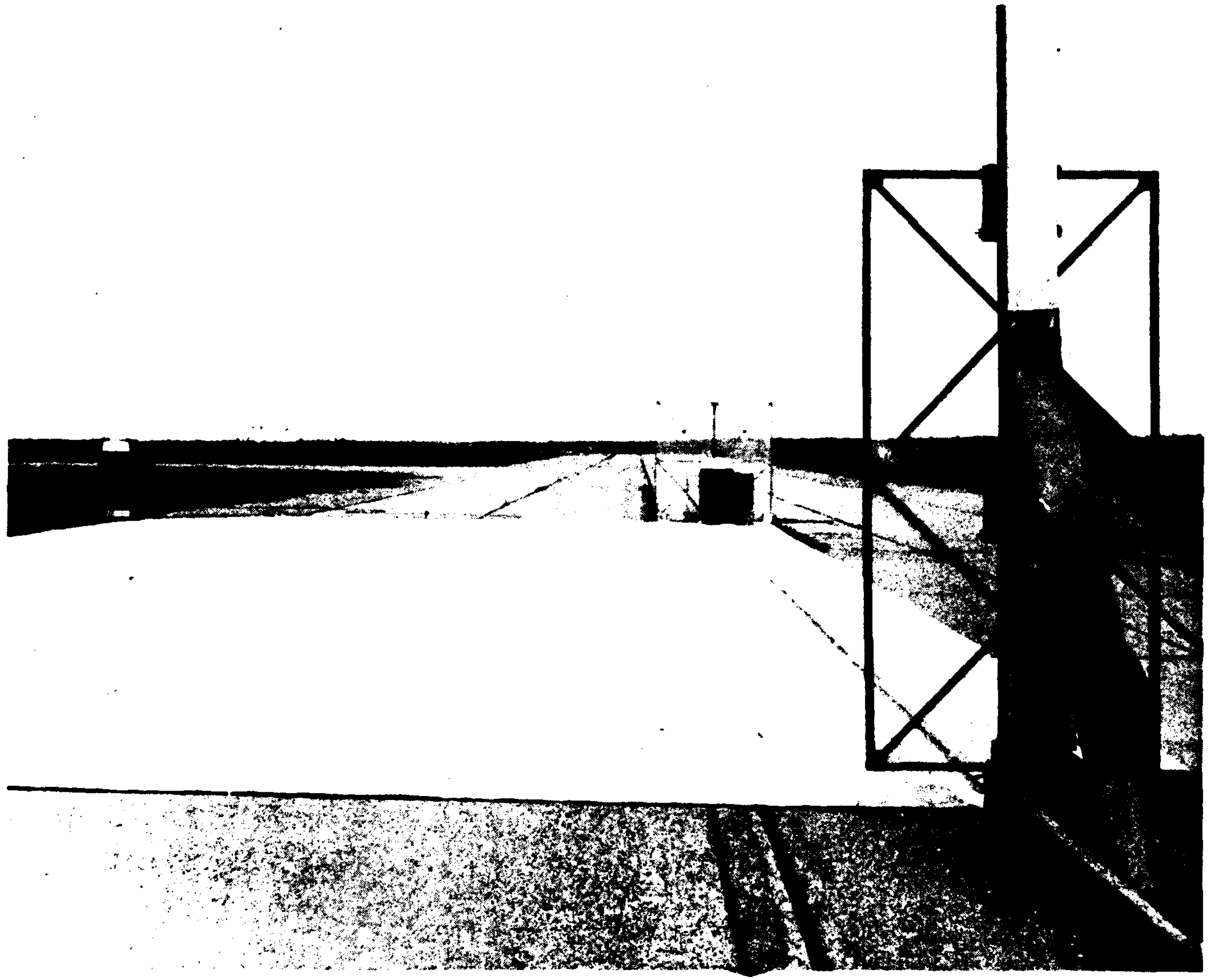


FIGURE 3-3. VIEW LOOKING TOWARD TOUCHDOWN

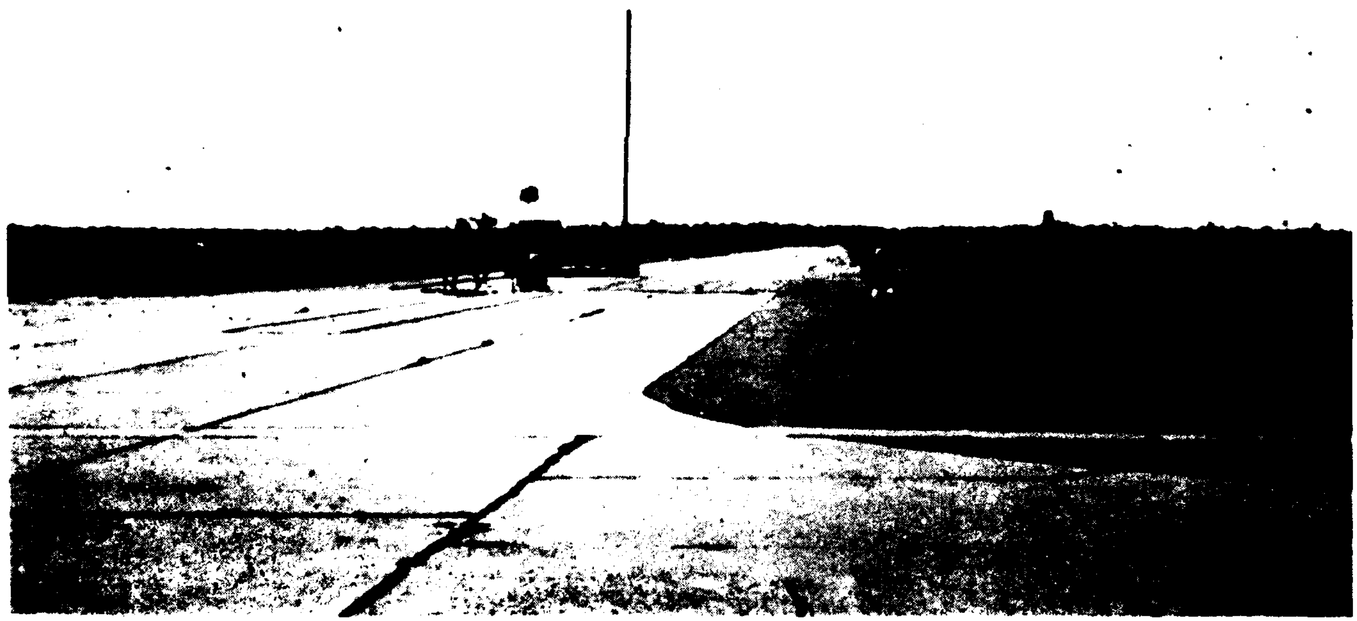


FIGURE 3-4. OVERALL VIEW OF TEST RANGE

4.0 TEST RESULTS

4.1 STATIC ACCURACY

The first series of measurements upon installation were made to verify system operation and performance. Station accuracy, both azimuth and elevation, were checked at several azimuth angles (-17, -9, 0, +9° and +17°) and at ranges from 20 to 900 feet. The data in Tables 4-1A, 4-1B, and 4-1C are examples of typical performance. Tables 4-1A and 4-1B shows Station #1 characteristics at zero degrees azimuth and at various elevation angles. Table 4-1C shows Station #2 performance from the maximum range positive azimuth through the maximum range negative azimuth angle. The average azimuth error for Station #1 is -0.026° and for Station #2 -0.0102°, with corresponding standard deviations of 0.0436 and 0.0704. All errors, except for one at 20 feet range and at a negative elevation angle with respect to the azimuth antenna, are generally well within ±0.1°. If the one excessive error is disregarded, then the Station's #2 average azimuth error becomes 0.0015 with a standard deviation of 0.0452.

In the 40 feet to 800 feet range sector, the average elevation error is 0.01° with a standard of deviation of 0.044°. The errors observed at 20 feet range were as large as 0.3°. But as explained later in Section 4.2, errors of this magnitude could be measured due to the simplified assumption that the antenna's center of rotation and center of radiation are coincident.

The relatively large angular errors so close-in only produces linear errors in order of an inch or so. Because the effects of these last errors are insignificant, no further investigation was made. However, one may conjecture that because the receiver is below azimuth centerline (about 0.5°), fringing effects from the metallic housing may distort the beam and cause the azimuth errors.

4.2 DYNAMIC TESTS

This series of tests was made in order to measure system performance under various approach profiles and multipath conditions. As mentioned earlier, a representative group of tests are reported here. These

are shown schematically in Figure 4-1 and tabulated in Table 4-2. The test results are shown in Figures 4-3 through 4-20. Also, specific tests aimed at examining and evaluating system performance under particular multipath and double bounce conditions were performed. Their results and analysis are discussed later in Sections 4.3 and 4.4.

Generally, two families of curves are plotted for each approach. First, the raw angle errors (Azimuth 1, Azimuth 2 and Elevation) are plotted as a function of range and secondly, the calculated X, Y, Z position coordinate errors are shown. For three runs, (see Figures 4-12, 4-13, and 4-14) typical glide slope approaches that might be followed in practice, the resultant computed range rates, $\dot{X}$ (range rate), $\dot{Y}$ (cross axis) and $\dot{Z}$ (height rate) are plotted as a function of range.

A standard "$\alpha - \beta$" tracking filter is used to produce velocity outputs from the raw position measurements. Although the data was taken with a 4 Hz cycle system, the velocity calculations are made on the assumption that the data will be provided at a 10 samples/second data update rate so the range rate computations are averaged over 10 samples, while the height and crosstrack velocities are averaged over 5 samples.

The effective averaging time, T_e of the "$\alpha - \beta$" filter equals NT_s where:

$$T_s = \text{time between samples}$$

$$N = \frac{4\alpha - \alpha\beta - 2\alpha^2}{2\alpha^2 + 2\beta - 3\alpha\beta}$$

α and β are dimensionless variables with β being determined by the following relationship:

$$\beta = \frac{\alpha^2}{2 - \alpha}$$

which is the optimum value of β in terms of α to minimize the total mean square error of both the position and the velocity outputs in the face of a ramp transient position input corrupted by independent noise on each sample.[1] Filter response time to a step position input is about 0.57 T_e to reach 63% of the input step and the response time for a step velocity input is about 1.85 T_e to reach 63% of the input step velocity.

For the range rate calculations with $T_s = 0.1$ second and N = 10, T_e = 1 second, and the filter constants are $\alpha = 0.13$ and $\beta = 0.0090$. Thus, for a step range input change, filter response time is 0.57 seconds and for a step velocity input change, the filter response time is 1.85 seconds. Similarly, for the height and crosstrack rate calculations T_s = 0.1 seconds, N = 5 and T_e = 0.5 seconds, and the filter constants are $\alpha = 0.255$ and $\beta = 0.0375$. Correspondingly, the height and crosstrack response times are 0.28 seconds for step position changes and 0.93 seconds for step velocity changes.

Because the high speed truck tests covered a small time period, the number of data samples was not adequate to permit 10 sample averaging. In this case, the velocity is obtained by averaging over 4 samples corresponding to the 4 cycles/second sample rate of CO-SCAN.

Because the linear accuracies are range related, the statistical properties for each parameter have been determined over 100 foot range sectors. These are recorded on each plot, and summarized in Table 4-3. Also, the composite values for each range sector are listed in Table 4-3. Similarly, Table 4-4 lists the 1 sigma values of the approach velocities for each range sector.

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[1] Benedict and Bordner, "Synthesis of an Optimal Set of Radar Track-While-Scan Smoothing Equations, "IRE Transactions on Automatic Control, Vol. AC-7, July 1962, p. 27.

Examination of Table 4-3 shows the 1 sigma range errors are well under 1 foot within a distance of 100 feet, while height and crosstrack errors are less than 0.5 foot at this range. In fact, the latter two, height and crosstrack position, maintain accuracies better than 1 foot at distances up to 500 feet and 3° elevation angle. These test results are consistent with the expected errors obtained by computer simulation of TRISCAN.

In the 600-675 feet range sector, the range errors have increased to almost 15 feet standard deviation on top of a bias error of about 22 feet. In this same range sector, the crosstrack errors are still under 1 foot while the height errors show a 1 foot bias with a 0.8 foot standard deviation.

At ranges up to 800 feet, the range error has increased to 33 feet standard deviation on a bias of 21.2 feet. As explained in Section 4.4, the significant portion of the errors are due to multipath effects and the geometric dilution of precision in the conversion from angular to rectangular coordinates.

Likewise, Table 4-4 shows one sigma range rate errors under 1 FPS in the range from 300 feet into touchdown. At distances of 500 feet, and elevation angles of 3°, the height and crosstrack errors are still relatively insignificant with values under 0.5 FPS. In the 600-675 feet range sector, the range rate errors have increased to 3.14 fps standard deviation. However, the crosstrack and height rate errors are still under 0.5 fps.

A group of runs were initially made with the ground reflecting screen only, and then repeated after the vertical reflectors were added behind the transmitter station and the receiver antenna. The last series of tests are the high speed truck runs.

Although the test plots are self-explanatory, some general observations and comments are summarized here:

1. Beyond 50 feet, the angle data of repeat runs with the vertical reflectors, appear to be somewhat noisier, but are essentially identical to the corresponding runs without vertical reflectors.

2. Within 50 feet, double bounce multipath tests with vertical reflectors produced larger azimuth noise errors with peak magnitudes of 0.6° compared to 0.2° under most other conditions.

3. With decreasing range starting at about 35 feet, elevation angular errors begin to increase reaching nominally 0.3° at 20 feet. This represents a 1 inch linear error of the receiver position with respect to the radiating antenna. The range is calibrated on the basis that the antenna center of rotation and center of radiation are coincident. However, since the receiver is well within the near field of the antenna, this assumption may be in error by an inch or so in these regions.[1] This error is insignificant for all practical purposes and could only be detected and isolated under the precise measurement procedures followed by this test program.

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[1] The near field is defined as a range less than $\frac{2d^2}{\lambda}$ or $\frac{2\ (25)}{.76}$ = 137 feet for the elevation antenna.

TABLE 4-1A

AZIMUTH 1 STATIC ACCURACY

RANGE (FEET)	HEIGHT (FEET)	AZIMUTH 1			
		MEASURED ANGLE	TRUE ANGLE	ERROR (DEG)	σ
800	35	-.005	0	+.005	.023
600	35	.034	0	-.034	.038
600	30	.016	0	-.016	.035
400	35	.028	0	-.028	.052
400	30	.005	0	-.005	.032
400	20	-.004	0	.004	.030
200	35	-.015	0	.015	.043
200	30	-.008	0	.008	.026
200	20	-.015	0	.015	.040
200	10	-.003	0	.003	.054
100	25	-.044	0	.044	.051
100	20	.032	0	-.032	.041
100	10	.025	0	-.025	.045
100	5	.053	0	-.053	.025
80	20	.094	0	-.094	.040
80	10	-.061	0	.061	.028
80	5	.035	0	-.035	.033
60	15	.019	0	-.019	.041
60	10	.027	0	-.027	.038
60	5	.026	0	-.026	.042
40	10	.040	0	-.040	.045
40	5	.034	0	-.034	.038
40	3.35	.081	0	-.081	.024
20	5	.056	0	-.056	.042
20	3.35	.090	0	-.090	.035
20	1.67	.142	0	-.142	.040

TABLE 4-1B
ELEVATION STATIC ACCURACY

RANGE (FEET)	HEIGHT (FEET)	ELEVATION MEASURED ANGLE	TRUE ANGLE	ERROR (DEG)	σ
800	35	2.557	2.507	-.050	.022
600	35	3.360	3.340	-.020	.031
600	30	2.819	2.865	.046	.069
400	35	4.914	5.005	.091	.080
400	30	4.280	4.294	.013	.026
400	20	2.854	2.864	.010	.024
200	35	9.952	9.933	-.019	.030
200	30	8.562	8.539	-.013	.024
200	20	5.675	5.713	.038	.078
200	10	2.900	2.868	-.032	.028
100	25	14.043	14.043	0	.033
100	20	11.319	11.226	.092	.045
100	10	5.657	5.723	.066	.026
100	5	2.862	2.861	-.001	.002
80	20	14.043	14.045	.002	.031
80	10	7.102	7.139	.037	.062
80	5	3.532	3.572	-.040	.061
60	15	14.093	14.049	-.044	.035
60	10	9.512	9.479	-.033	.029
60	5	4.666	4.759	.093	.071
40	10	14.078	14.070	-.009	.036
40	5	7.095	7.126	.030	.032
40	3.35	4.781	4.798	.017	.024
20	5	13.737	14.037	.300	.077
20	3.35	9.298	9.539	.241	.034
20	1.67	4.523	4.764	.241	.054

TABLE 4-1C

AZIMUTH 2 STATIC ACCURACY

RANGE (FEET)	HEIGHT (FEET)	AZIMUTH 2			
		MEASURED ANGLE	TRUE ANGLE	ERROR (DEG)	σ
800	35	-17.800	-17.749	.051	.060
600	35	-16.801	-16.797	.004	.063
600	30	-16.886	-16.797	.088	.074
400	35	-14.838	-14.900	-.062	.050
400	30	-14.838	-14.900	-.062	.042
400	20	-14.972	-14.900	.071	.042
200	35	- 9.327	- 9.301	.026	.041
200	30	- 9.236	- 9.301	-.066	.047
200	20	- 9.305	- 9.301	.004	.050
200	10	- 9.274	- 9.301	-.027	.039
100	25	1.165	1.197	.031	.047
100	20	1.175	1.197	.022	.032
100	10	1.280	1.197	-.083	.035
100	5	1.220	1.197	-.023	.033
80	20	5.964	5.958	-.006	.042
80	10	5.956	5.958	.002	.048
80	5	5.884	5.958	.073	.040
60	15	-16.627	-16.635	-.008	.071
60	10	-16.670	-16.635	.035	.065
60	5	-16.639	-16.635	.004	.059
40	10	- 5.336	- 5.295	.042	.032
40	5	- 5.303	- 5.295	.008	.053
40	3.35	- 5.231	- 5.295	-.014	.034
20	5	13.169	13.135	-.034	.059
20	3.35	13.173	13.135	-.039	.075
20	1.67	13.438	13.135	-.303	.105

TABLE 4-2

DYNAMIC TEST RUN SUMMARY

RUN NO.	RANGE (FEET) START	RANGE (FEET) END	HT/G-S	FIGURE	COMMENTS
245-15	60	17	5'	4-2	↑
245-56	230	52	10'	4-3	
245-21	450	65	20'	4-4	GROUND REFLECTING SCREENS
245-18	60	16	3°	4-5	
245-24	670	52	3°	4-6	
245-59	335	52	6°	4-7	↓
245-101	45	16	2'	4-8	↑
245-91	60	20	5'	4-9	
245-72	230	52	10'	4-10	VERTICAL AND
245-66	450	65	20'	4-11	GROUND REFLECTING SCREENS
245-88	60	23	3°	4-12	
245-62	670	52	3°	4-13	
245-69	335	52	6°	4-14	↓
	HIGH SPEED TRUCK TESTS				
245-174	700	200	15'	4-15	30 MPH
245-177	700	200	15'	4-16	15 MPH
245-180	700	300	15'	4-17	30 MPH - FAST STOP
245-185	700	200	10'	4-18	30 MPH
245-189	700	200	10'	4-19	15 MPH
245-191	700	300	10'	4-20	30 MPH - FAST STOP

RUN	245-15		245-56		245-21		245-18		245-24		245-59		245-101	
RANGE START/END	60'/17'		230'/52'		450'/65'		60'/16'		670'/52'		335'/52'		45'/16'	
HEIGHT/GS	5'		10'		20'		3°		3°		6°		2'	
RANGE SECTOR	BIAS	1 σ	BIAS	1σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ
600/675									-17.2	14.46				
500/600									1.45	12.52				
400/500					8.69	6.52			3.6	7.5				
300/400					6.10	5.81			3.5	4.59	-.77	2.77		
200/300			1.73	2.63	1.00	2.64			2.56	2.29	-.84	2.26		
100/200			-.15	.81	-.38	.85			.66	1.04	-.75	.75		
∠ 100	.18	.19					.19	.19					.20	.29

TABLE 4-3A. RANGE ERRORS (FEET)

RUN	245-91		245-72		245-66		245-88		245-62		245-69		COMPOSITE	
RANGE START/END	60'/20'		230'/52'		450'/65'		60'/23'		670'/52'		335'/52'			
HEIGHT/GS	5'		10'		20'		3°		3°		6°			
RANGE SECTOR	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ
600/675									-22	13.15			-19.6	13.81
500/600									.69	13.60			1.03	13.06
400/500					10.16	8.40			3.55	7.57			6.5	7.5
300/400					4.66	5.46			2.25	4.05	.61	3.14	2.73	4.3
200/300			1.62	2.41	.67	2.46			2.23	2.23	.38	2.41	1.17	2.42
100/200			.10	.83	-.29	.82			.36	.27	-.42	.78	-.1	.77
∠ 100	.10	.19					.13	.16					.16	.20

TABLE 4-3A. RANGE ERRORS (CONT'D.)

RUN	245-15		245-56		245-21		245-18		245-24		245-59		245-101	
RANGE START/END	60'/17'		230'/52'		450'/65'		60'/16'		670'/52'		335'/52'		45'/16'	
HEIGHT/GS	5'		10'		20'		3°		3°		6°		2'	
RANGE SECTOR	BIAS	1 σ	BIAS	1σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ
600/675									-.27	.43				
500/600									-.12	.35				
400/500					.24	.35			-.09	.25				
300/400					-.12	.28			-.25	.22	-.12	.24		
200/300			.05	.19	-.06	.19			.06	.2	-.13	.18		
100/200			.01	.11	-.01	.12			.08	.11	-.02	.11		
∠100	.02	.03					.05	.03					.05	.06

TABLE 4-3B. CROSSTRACK ERROR (FEET)

RUN	245-91		245-72		245-66		245-88		245-62		245-69		COMPOSITE	
RANGE START/END	60'/20'		230'/52'		450'/65'		60'/23'		670'/52'		335'/52'			
HEIGHT/GS	5'		10'		20'		3°		3°		6°			
RANGE SECTOR	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ
600/675									-.34	.45			-.31	.44
500/600									-.15	.32			-.14	.34
400/500					.17	.36			-.14	.23			.05	.30
300/400					-.16	.31			-.27	.23	-.16	.20	-.18	.25
200/300			.02	.20	-.15	.20			.08	.22	-.06	.17	-.02	.19
100/200			.00	.11	-.04	.12			.06	.05	-.01	.11	.01	.10
∠100	.02	.05					.05	.07					.04	.05

TABLE 4-3B. CROSSTRACK ERROR (CONT'D.)

RUN	245-15		245-56		245-21		245-18		245-24		245-59		245-101	
RANGE START/END	60'/17'		230'/52'		450'/65'		60'/16'		670'/52'		335'/52'		45'/16'	
HEIGHT/GS	5'		10'		20'		3°		3°		6°		2'	
RANGE SECTOR	BIAS	1 σ	BIAS	1σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ
600/675									-1.03	.78				
500/600									- .03	.70				
400/500					.65	.44			.24	.44				
300/400					.32	.43			.30	.29	-.24	.31		
200/300			.03	.16	-.02	.35			.19	.21	-.11	.25		
100/200			-.04	.14	-.16	.25			0	.11	-.10	.11		
∠ 100	-.03	.05					-.02	.05					-.06	.06

TABLE 4-3C. HEIGHT ERROR (FEET)

RUN	245-91		245-72		245-66		245-88		245-62		245-69		COMPOSITE	
RANGE START/END	60'/20'		230'/52'		450'/65'		60'/23'		670'/52'		335'/52'			
HEIGHT/GS	5'		10'		20'		3°		3°		6°			
RANGE SECTOR	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ
600/675									-1.12	.74			-1.08	.76
500/600									-.06	.753			- .05	.73
400/500					.55	.53			.28	.44			.43	.46
300/400					.14	.44			.20	.27	.61	.53	.22	.38
200/300			-.12	.20	-.13	.35			.27	.17	-.23	.35	- .02	.26
100/200			-.08	.15	-.22	.22			.02	.08	-.10	.12	- .09	.15
∠100	-.05	.06					-.02	.05					-.04	.05

TABLE 4-3C. HEIGHT ERROR (CONT'D.)

RUN	245-174		245-177		245-180		245-185		245-189		245-191		COMPOSITE	
RANGE START/END	700'/200'		700'/200'		700'/300'		700'/200'		700'/200'		700'/300'			
HEIGHT/GS	15'		15'		15'		10'		10'		10'			
RANGE SECTOR	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ	BIAS	1 σ
600/675	-18.96	12.01	-4.90	16.21	-13.51	12.92	1.28	22.04	1.47	23.14	8.92	27.33	-4.28	18.94
500/600	- .59	16.26	1.27	11.77	- 2.49	14.38	17.19	16.83	6.00	17.86	11.36	15.87	5.46	15.50
400/500	- 3.47	6.49	2.57	8.31	- 3.72	9.82	-8.12	5.40	-5.03	12.91	-2.62	7.60	-3.40	8.42
300/400	1.57	6.59	-.43	6.03	1.87	5.83	1.67	4.91	-2.38	6.08			.46	5.89
200/300	1.63	3.33	.47	3.76	2.21	3.11	3.40	2.73	-1.95	4.54			1.15	3.49
100/200														
∠100														

TABLE 4-3D. TRUCK TEST RANGE ERRORS (FEET)

RANGE SECTOR (FEET) / RUN	∠100	100/ 200	200/ 300	300/ 400	400/ 500	500/ 600	600/ 675
245-88 3°GS							
$\dot{X}$ MEAN	1.34						
1 SIGMA	.06						
$\dot{Y}$ MEAN	0						
1 SIGMA	.05						
$\dot{Z}$ MEAN	.07						
1 SIGMA	.03						
245-62 3°GS							
$\dot{X}$ MEAN		2.29	2.3	2.32	2.3	1.62	2.42
1 SIGMA		.14	.42	.75	1.47	2.46	3.14
$\dot{Y}$ MEAN		0	-.01	0	0	.01	.02
1 SIGMA		.05	.11	.11	.12	.16	.24
$\dot{Z}$ MEAN		.12	.12	.12	.12	.08	.14
1 SIGMA		.06	.09	.15	.26	.33	.43
245-69 6°GS							
$\dot{X}$ MEAN	2.42	2.41	2.52				
1 SIGMA	.11	.22	.56				
$\dot{Y}$ MEAN		0	0				
1 SIGMA		.06	.1				
$\dot{Z}$ MEAN		.25	.25				
1 SIGMA		.06	.20				

TABLE 4-4. VELOCITY ERRORS (FT/SEC)

4.3 DOUBLE BOUNCE EFFECTS

System performance, under "double bounce" geometry conditions, was initially investigated with tilted and parallel screens behind the receiver and transmitter. The tilted screens, although flat, is a fair representation of the reflection surfaces that may be encountered by a V/STOL approaching the landing zone onboard ships. Slow approaches (under 1 foot/second) were made with the screens, first, tilted 10° and later repeated with a 20° tilt of the screens. The screens were then positioned vertically and the remainder of the tests were made with this configuration. Both the receiver IF signals and the system angular accuracies were observed.

Extensive probing did not uncover any noticeable effects at the expected reflection points, but relatively large azimuth angle perturbations of ±0.6° were found at ranges under 25 feet. As discussed earlier in Section 3.3, tilted screen double bounce multipath effects occur over a limited range sector. Therefore, further tests were performed with screens positioned vertically. This provided a geometry that theoretically would continuously maintain the double bounce reflection conditions regardless of range; and permit a longer and more detailed observation of the double bounce reflection effects.

The receiver was placed at the same height (at this height double bounce conditions would be at a maximum) as the transmitter antenna and very slow approaches were run toward the ground station. The azimuth angle showed increasing noise type errors (plus and minus excursions increased) as the receiver moved within 40 feet of the transmitter.

Figure 4-21 shows the error increasing to ±0.6° peak at about 30' range and then decreasing as the range is further reduced. Although the effect on linear position may be considered minor, being in the order of several inches, it is significant compared to the 1 foot target accuracy requirement. Therefore, further investigation was made to determine the cause. As mentioned earlier, the vertical screen arrangement provided greater possibilities for double bounce effects and the investigation was made with this configuration.

Preliminary analysis indicated that RF leakage from the ground station was a potential factor.* Therefore, special waveguide runs and brackets were fabricated to permit installation of the attenuator inside the station cabinet and the closing of the doors effectively eliminating the RF leakage. A period of several weeks passed while the fabrication took place; and, also during this time, winds at the test site damaged the reflector screens. The screens were reinstalled, stiffened and securely fastened to the frame holding them.

After installation of the new waveguide, the tests were rerun -- and the effects noticed earlier were gone. To verify that the changes had indeed been effective, the original equipment setup was reinstalled and tests, again, repeated -- and the original effects were not duplicated. Consequently, exhaustive and repetitive measurements were made in an attempt to repeat the earlier effects. Because the screens had been reworked, they were reoriented in many ways along with various station configurations in the endeavors to reproduce the earlier results. Finally, after the transmitter screens were tilted forward about 6°, similar results to the earlier ones were seen and it made little difference after the RF tight station was reinstalled. The results are shown in Figure 4-22. In all likelihood, when the original tests were made, the top of the screens may have also been leaning forward, because they had not been rigidly fastened to the support base.

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* Due to the short distances between receiver and transmitter, RF attenuators were installed in the ground station to reduce transmitted power to avoid saturating the receiver (because this receiver does not have an automatically controllable input attenuator). The attenuator was placed outside the station cabinet and flexible waveguides attached to it and the high power magnetron. Consequently, there was RF leakage present due to the combination of open cabinet and leaky waveguide joints.

Double bounce multipath test results, Figures 4-21 and 4-22, show the magnitude of the angular errors varies with receiver range. The errors increase with decreasing range, reach a peak and then decrease with further reduction in range. This can be understood by reference to the double bounce geometry illustrated in Figure 4-23, that traces the indirect path followed by the peak of the antenna beam. The figure illustrates the situation where the indirect (double bounce multipath signal) path of the beam peak is directed right into the receiver antenna. At other receiver ranges, the resultant geometry causes the beam peak to follow a path that crosses either in front of or behind the receiver antenna.

As shown in Figure A-2, the elevation coverage of the azimuth beam is over 20 degrees. Thus, some double bounce energy would be detected by the receiver regardless of range, especially for the case of vertical (0 degree tilt) reflectors where the reflected signal is continuously received. As the receiver approaches the transmitter, there is a build-up of received double bounce energy until the beam peak is intercepted, and then a fall off with further receiver movement. Therefore, when the double bounce signals become large enough to introduce measurement errors, the errors would gradually increase, reach a peak and finally decrease as the receiver continues to move toward the transmitter; and as noted above, these results occurred during the double bounce test runs.

Because of receiver motion, the combined signal fluctuates due to the changing phase relationship between the reflected and direct signals. Pulses at the beginning of a beam passage are affected differently than pulses at the end of the beam passage, effectively distorting the beam envelope. This can cause an effective beam shift and consequently an error in the angle measurement.

Beam envelope distortion due to RF phase variation is dependent on the relative magnitude and the initial phase between the direct and reflected signals, and receiver velocity. The distortion is most pronounced when the phase difference is about 180 degrees, and the composite signal amplitude can change rapidly with small changes in phase between the direct and reflected signals. Also, higher velocities would increase the phase differences across the beam producing greater beam noise and larger angle measurement errors.

For the double bounce situation, the change in path length difference (between the direct and reflected signals) occurs at twice the rate of change in the direct path length. At 15.5 GHz, a wavelength equals 0.76" and the path length difference goes through a complete cycle, corresponding to the relative phase change of 360°, for a 0.38" movement of the receiver. During the double bounce test runs, the approach velocity was between 0.3 to 0.5 feet per second. Nominal beam dwell time was about 3.25 milliseconds. Accordingly, the receiver displacement during the beam dwell was 0.02 inches and there was a 19 degree phase shift change between the direct and reflected signals across one beam.

Figure 4-24 contains a series of plots that show how the crossover distance (the spacing between the indirect path of the beam peak and the receiver at the fixed receiver height) varies with receiver range.

The peak of the beam is assumed to be 5° above the horizontal and the results are shown for reflector tilt angles from 7 to 8 degrees. As can be seen, that except for a very narrow band of reflector tilt angles, the reflected beam peak is always directed away from the receiver (either front of or behind) so that low level double bounce signals - insufficient to cause errors - are received. Consequently, it could be (as was inadvertently shown) very difficult to experimentally reproduce these exacting conditions to test for double bounce effects.

Plots for different tilt angles indicates noise errors would gradually increase with decreasing range, reach a peak at crossover and then start to fall as the range decreases further. This effect was observed, both in the original double bounce tests, Figure 4-21 and the repeat shown in Figure 4-22. As the curves show, a very small tilt angle change (e.g., 7.3° to 7.4°)[1] changes crossover from 15 to 25', and this probably explains the differences between the curves.

A factor to be considered in assessing double bounce (or any other interfering signal source) effects is the bandwidth of the receiving system.

Because system accuracy degradation from interfering signals (due to either multipath or double bounce) results from pulse distortion, interfering signals received after the pulse are not consequential since the processing circuitry ignores any pulses until the next valid pulse is expected, which is well after any multipath or interfering signals could be received.

The present receiver is band limited by the video amplifier that has a 3 MHz bandwidth, and the pulse characteristics are 300 nanosecond width with 120 nanseconds rise and fall times. Consequently, only an interfering pulse that is received within 300 nanoseconds after the direct signal can possibly introduce errors, or if the interfering signal travels an additional 300 feet before reception.

If the pulse rise time and detector response times are considered, the interfering pulse would have to be received not more than 250 nanoseconds after the direct signal to affect system accuracy. For the double bounce situation, the aircraft would have to be within 125 feet of the transmitter. Since the expected reflection points, with the tilted screens, are at longer ranges, there should not be any double bounce effects and, as mentioned earlier, the tests did not uncover any effects at these ranges.

---

[1] Note a tilt angle change from 7.5 to 7.6 changes the crossover from 45' to over 100 feet.

As shown by the tests, the double bounce effects occurred under 40 feet from the station. With a peak error of 0.6° (run 120) at 30 feet, the corresponding peak linear error is about 0.7 feet.

In summary, these tests have addressed the problem of severe multipath and have shown that the errors, although comparable, are within the target accuracy requirements.

4.4 MULTIPATH EFFECTS

The effects of RF multipath were investigated at the longer ranges, particularly in the ranges beyond 600 feet. Run 76, see Figure 4-25, taken principally to search for multipath, was a level flight approach from 830 to 600 feet range. The receiving antenna was at 36.7 feet height and the aluminum screen covering the first 100 feet in front of the ground stations was in place. After the triangulation calculations, where the effects of angular effors are multiplied by the geometrical conversion to linear parameters, the multipath effects become readily apparent. In this sector, Azimuth 1 had a bias error of 0.07° with a 0.07° 1 sigma deviation and Azimuth 2 had a -0.01° bias error and 0.095° 1 sigma deviation. Correspondingly, the distance error had a bias error of 21.2 feet with 33 feet 1 sigma deviation.

A plot of range error versus range shows two basic components, a range dependent cyclical error and the usual scan to scan random error. In this range sector, the error contributions from each source are about equal and are approximately 100 feet peak to peak each. Also shown in Figure 4-25 are the azimuth angle errors of the two ground stations. It is obvious that the peaks of large range error corresponds to peak errors of Azimuth 2. Although Station #1 shows similar cyclical errors, its contribution is minor, as compared to Station #2, due to the geometry. Azimuth 1 errors tend to be positive and Azimuth 2 errors tend to be negative in this run -- probably boresite related.

The test site sloped from side to side about 3 inches in 24 feet which is .6°. A beam reflected by this surface will be squinted 1.2° from the incident direction. Assume the pattern of the azimuth beam to be of the form

$$\frac{\sin (k \sin \theta)}{k \sin \theta}$$

Correspondingly, the reflected beam is represented by $\sin [k \sin (\theta + 1.2)]/ k \sin (\theta + 1.2)$. The combinations of the direct and reflected beams are plotted in Figure 4-26 for in-phase and out-of-phase conditions. The reflected beam was assigned an amplitude factor of .25 (reflection coefficient .8, pattern factor .3). The condition plotted shows that the beam centroid is shifted about .33 degrees peak. This compares closely with a peak-to-peak of 0.3° shift of the Azimuth 2 test data.

As confirmation that this is the cause of the errors, the error plots should conform in period to the relative phase of the direct and ground reflected signals. This is illustrated in Figure 4-27 that shows the angle error plots with the resultant field superimposed.

In summary, it has been shown that the periodic error in Run 76 is attributable to steering of the radiated beam due to multipath reflections from the sloped test site.

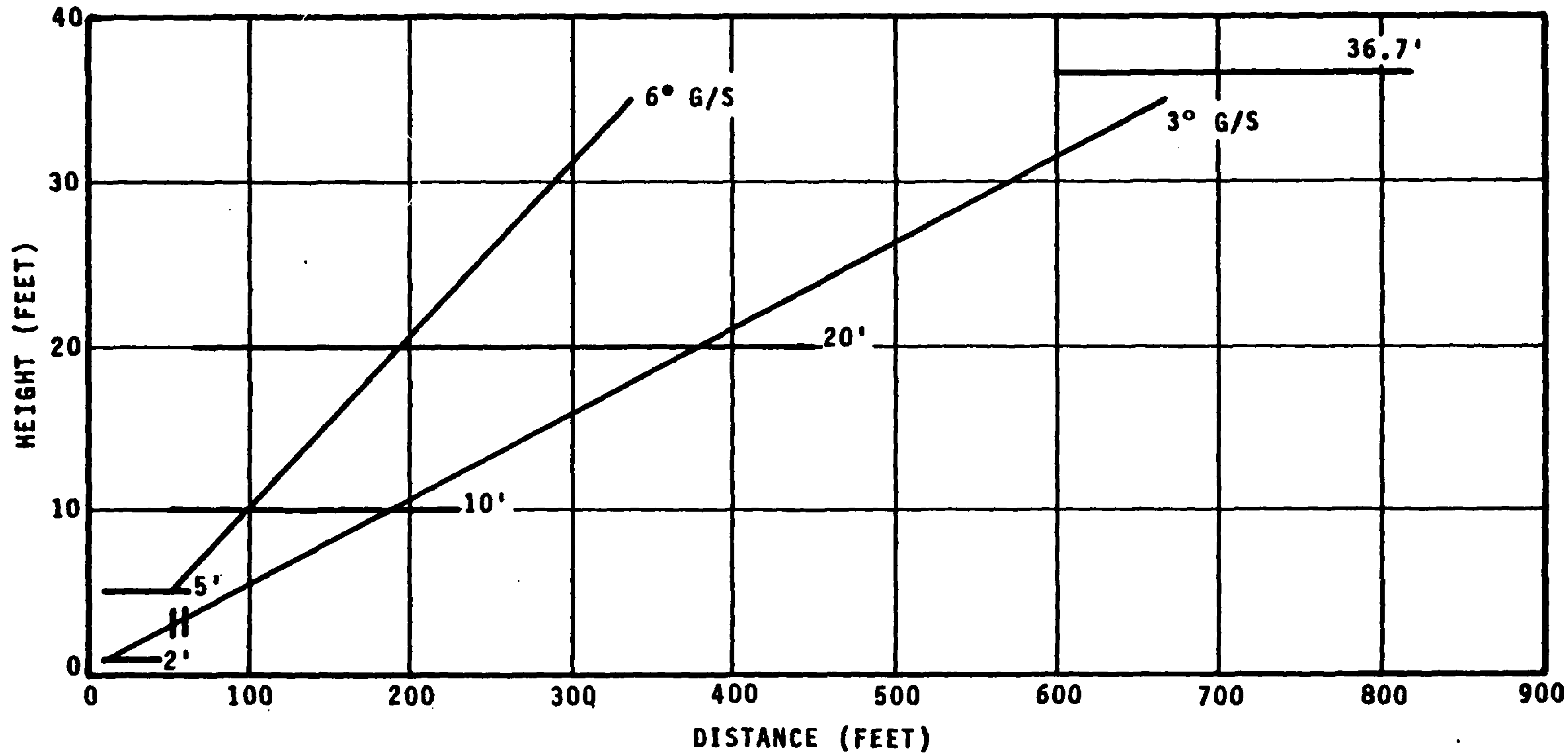


FIGURE 4-1. APPROACH PROFILES OF REPRESENTATIVE TEST RUNS

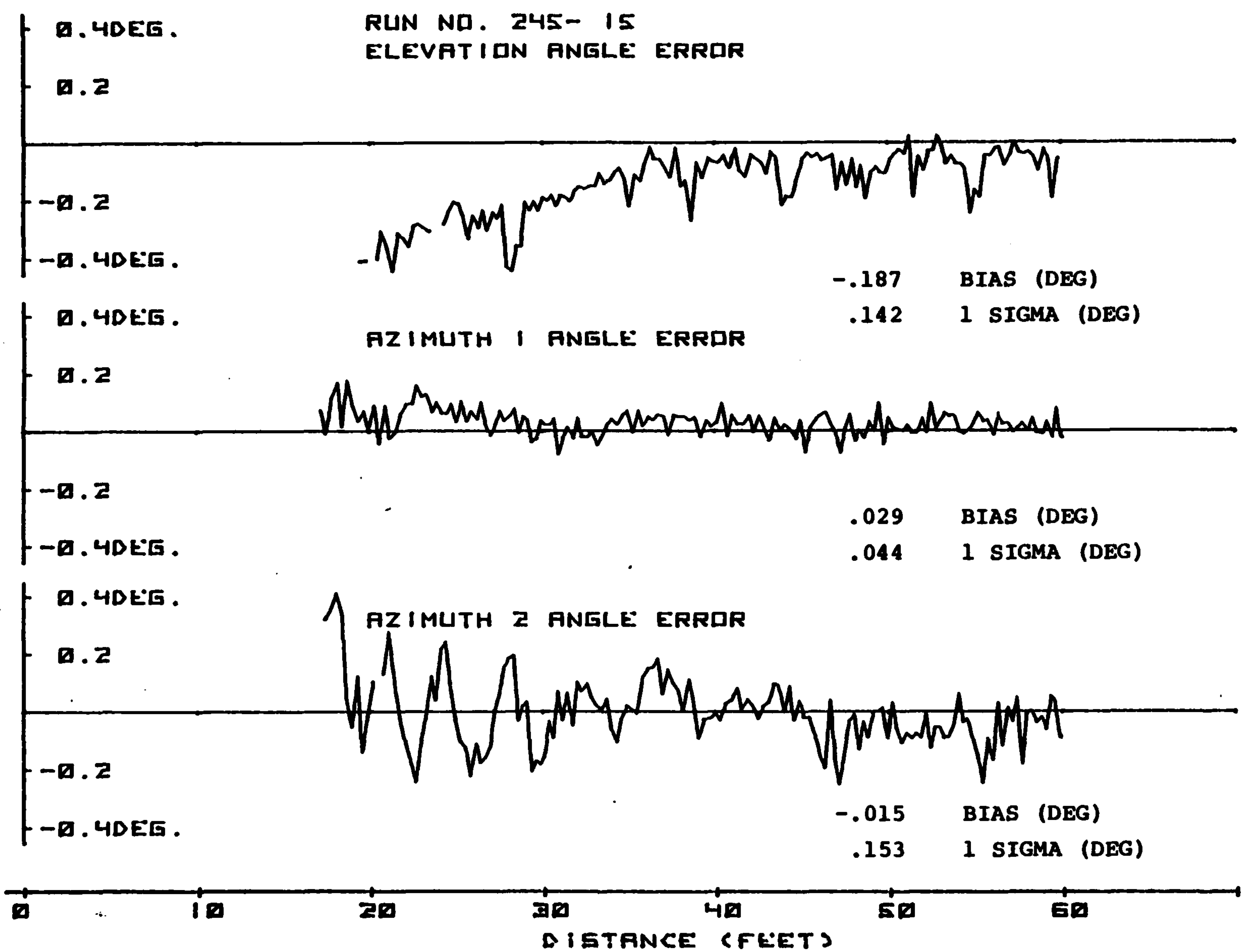


FIGURE 4-2A. 5' HEIGHT

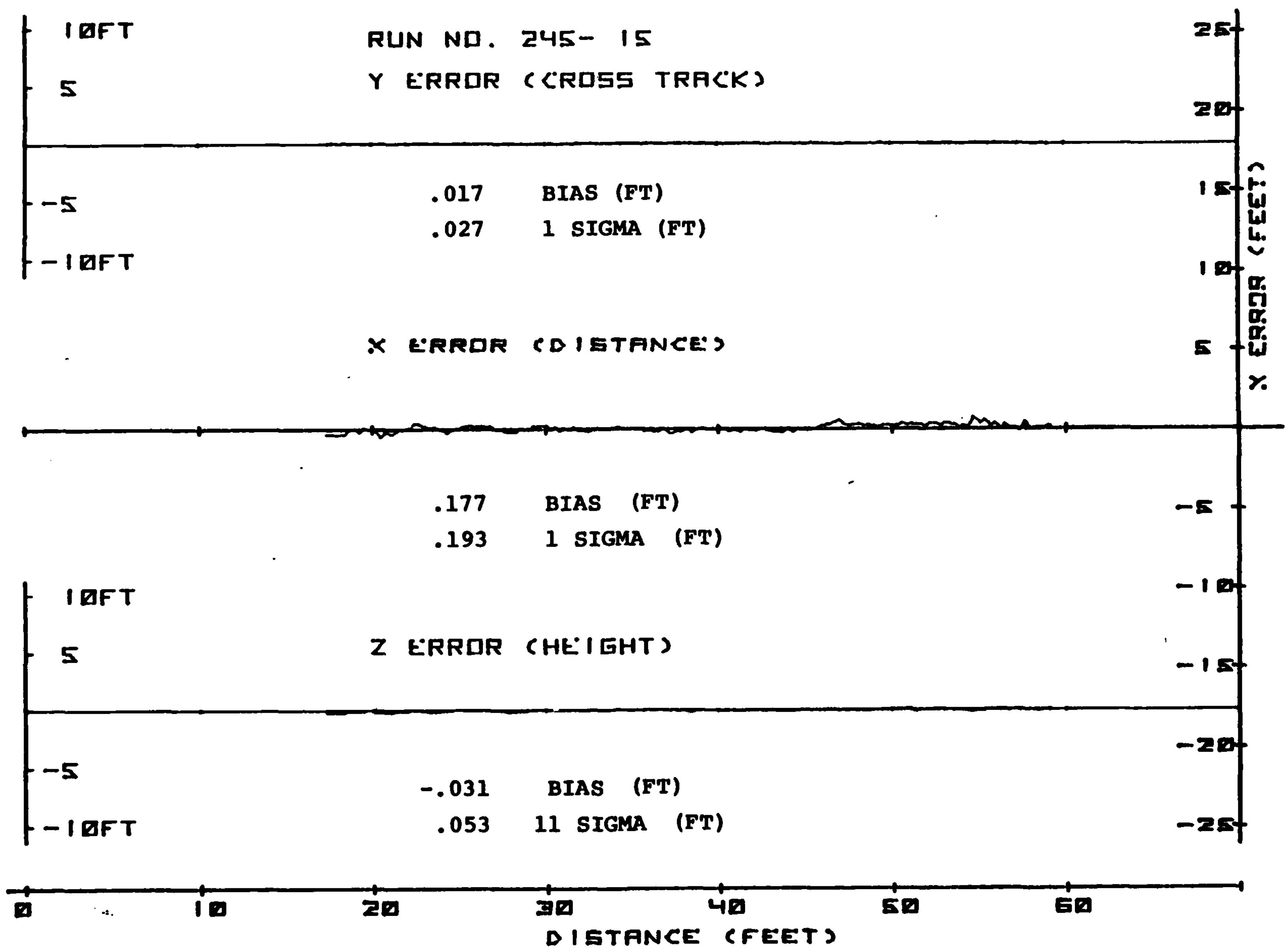


FIGURE 4-2B. 5' HEIGHT

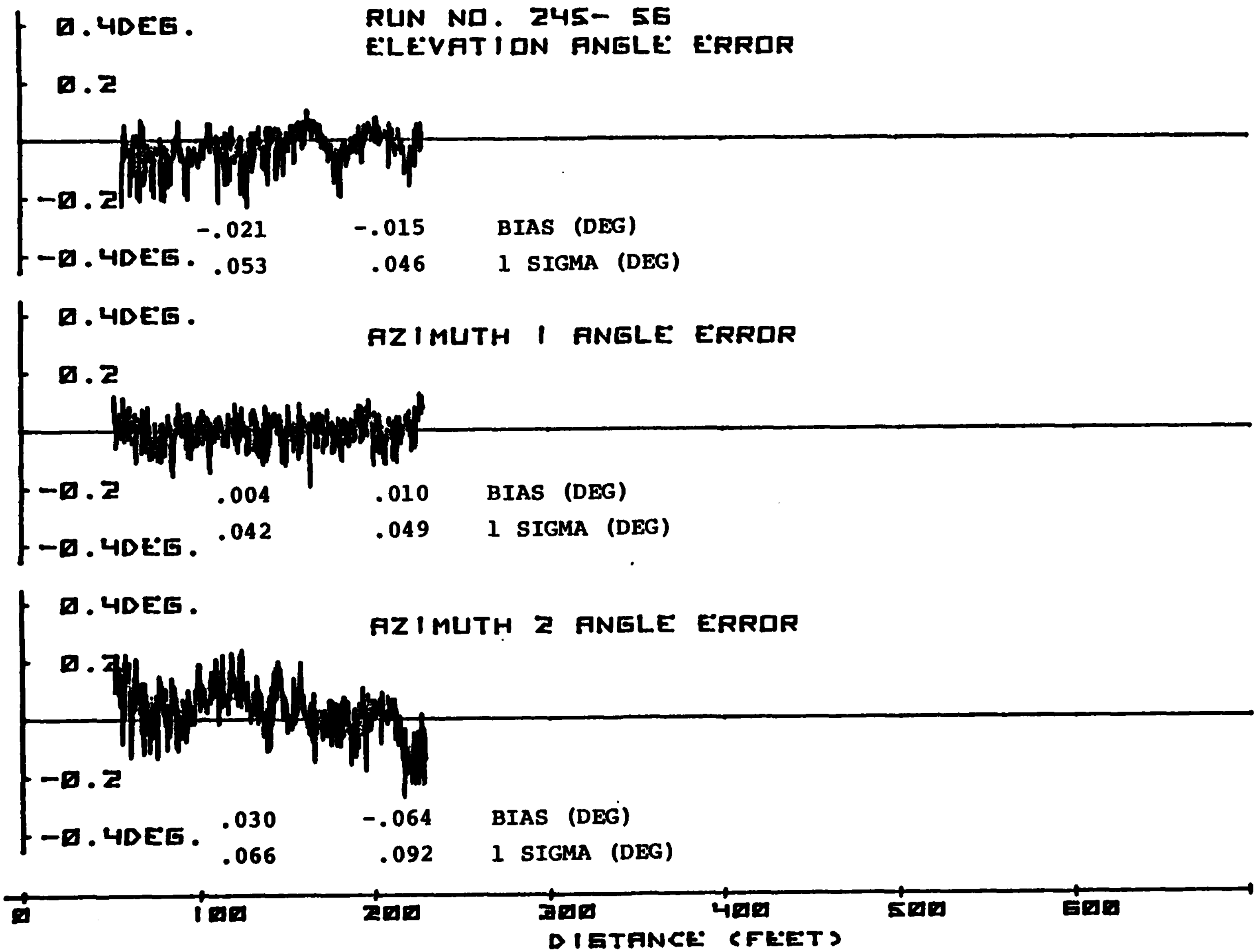


FIGURE 4-3A. 10' HEIGHT

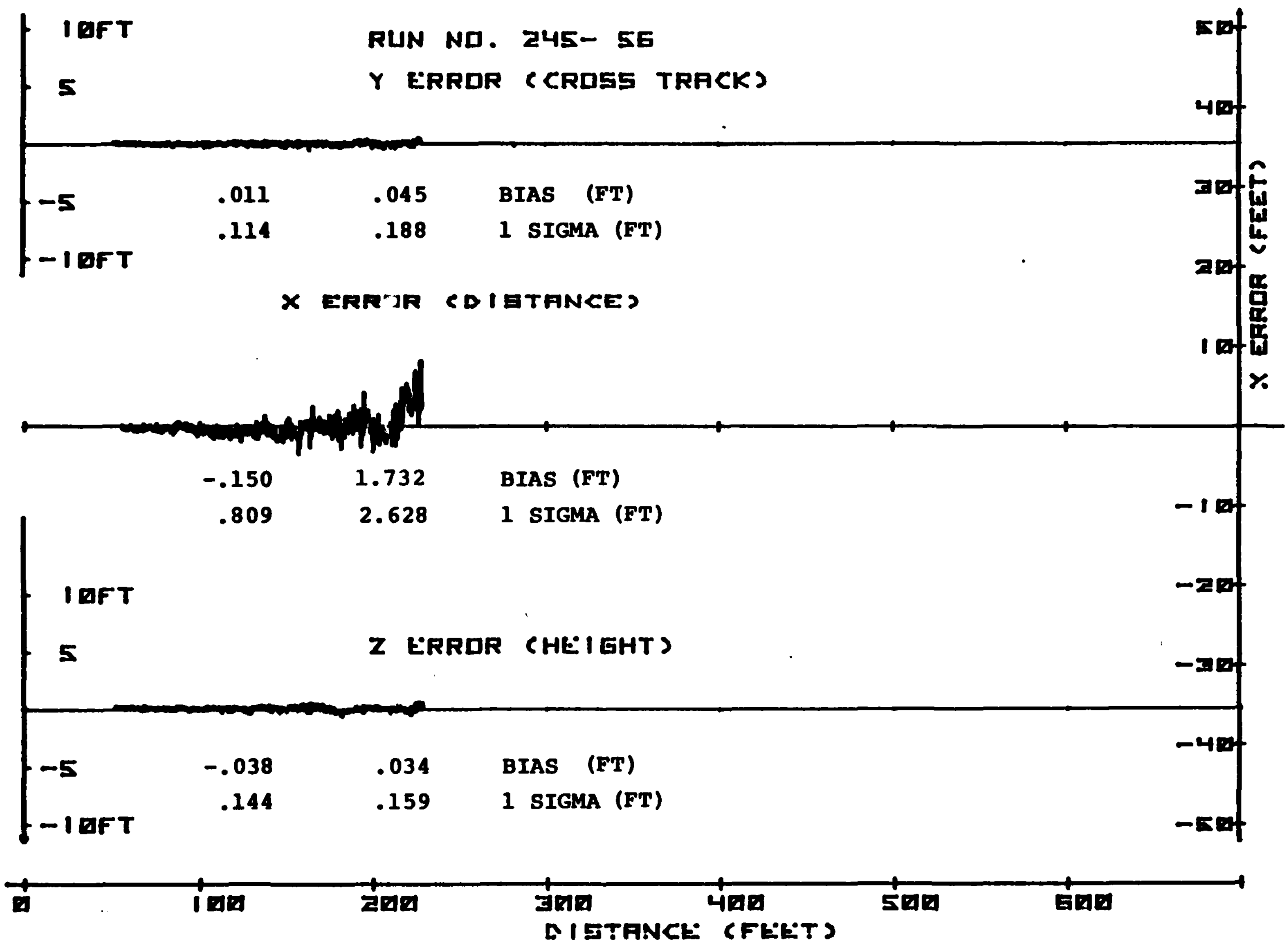


FIGURE 4-3B. 10' HEIGHT

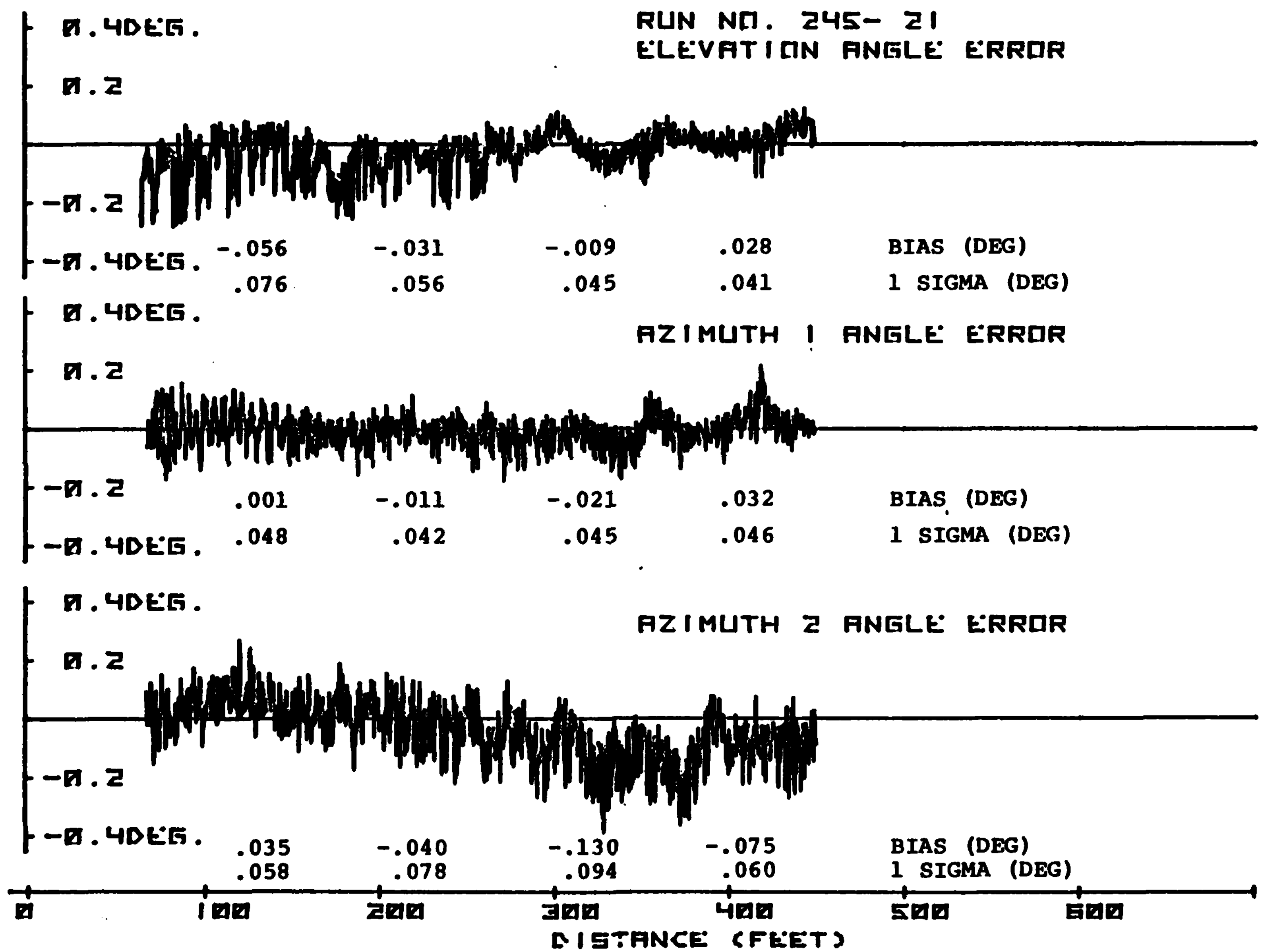


FIGURE 4-4A. 20' HEIGHT

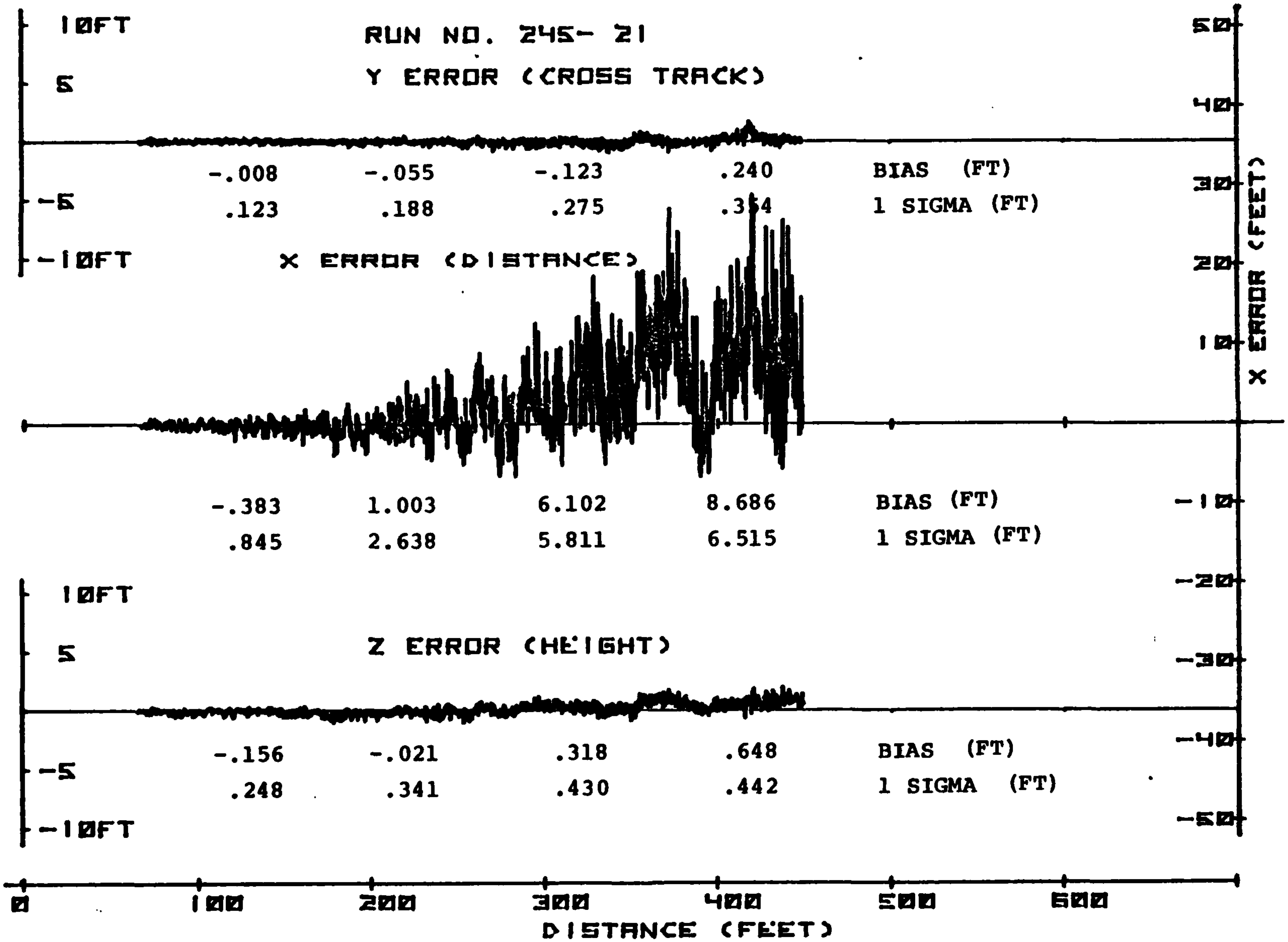


FIGURE 4-4B. 20' HEIGHT

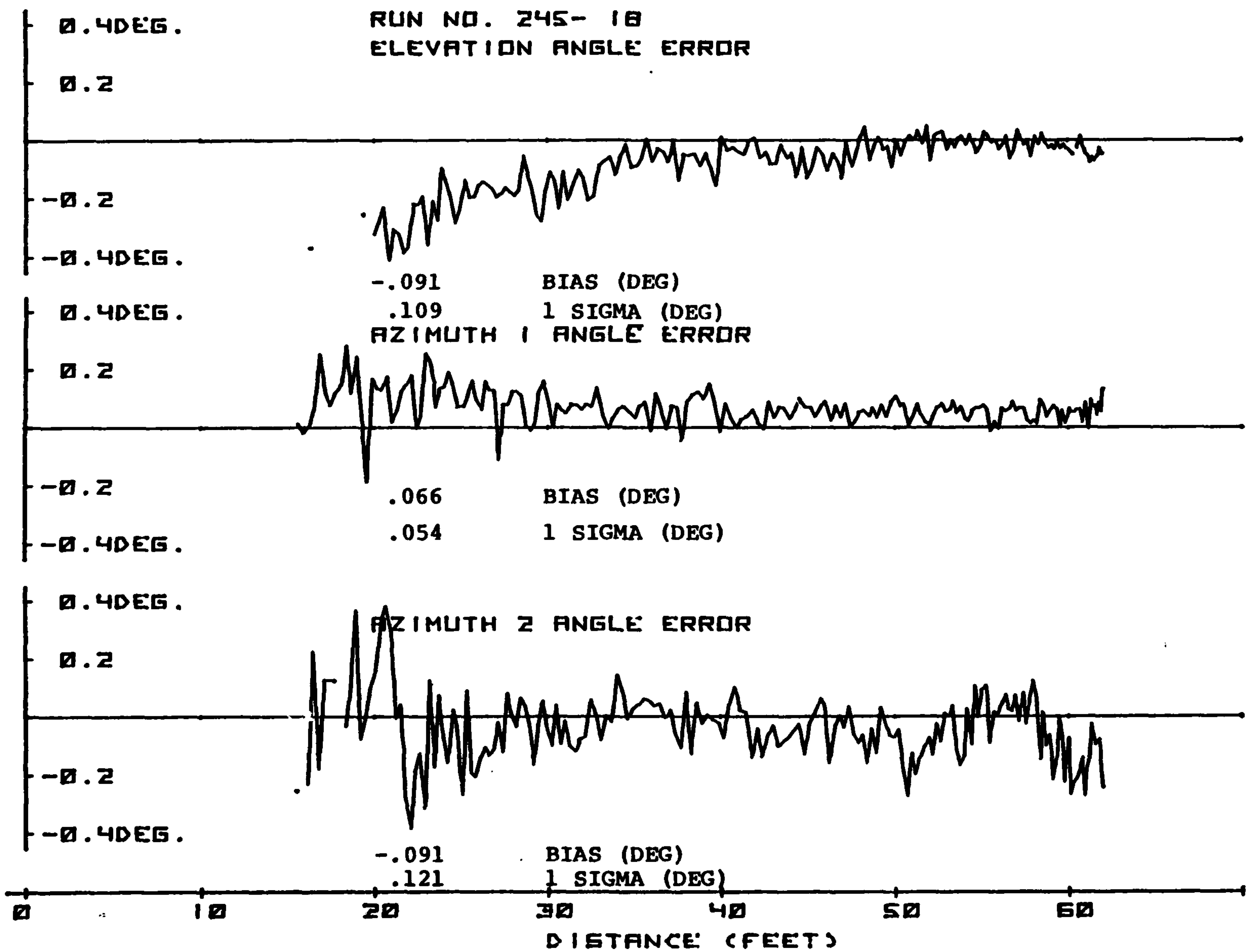


FIGURE 4-5A. 3° GLIDE SLOPE

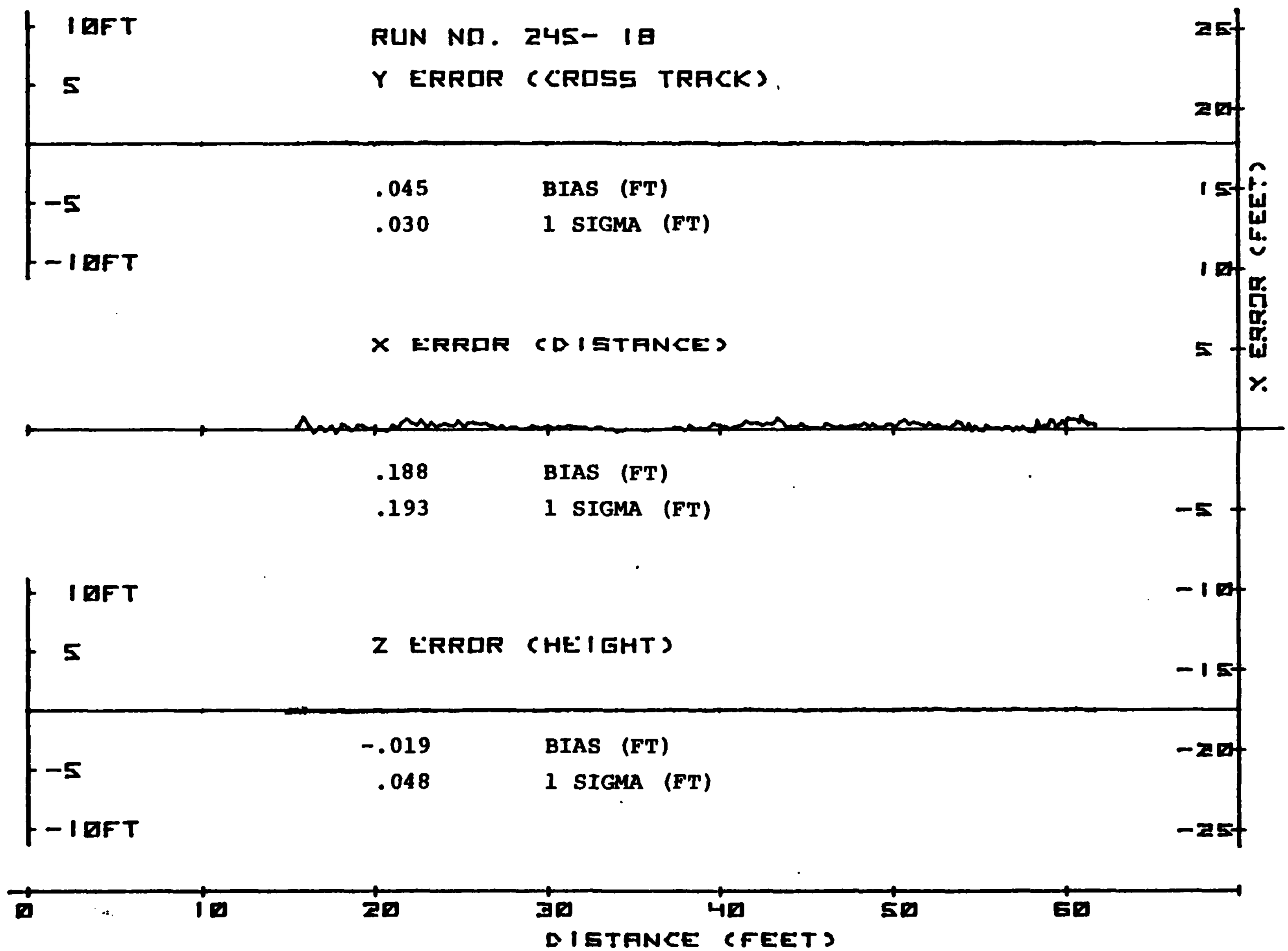


FIGURE 4-5B. 3° GLIDE SLOPE

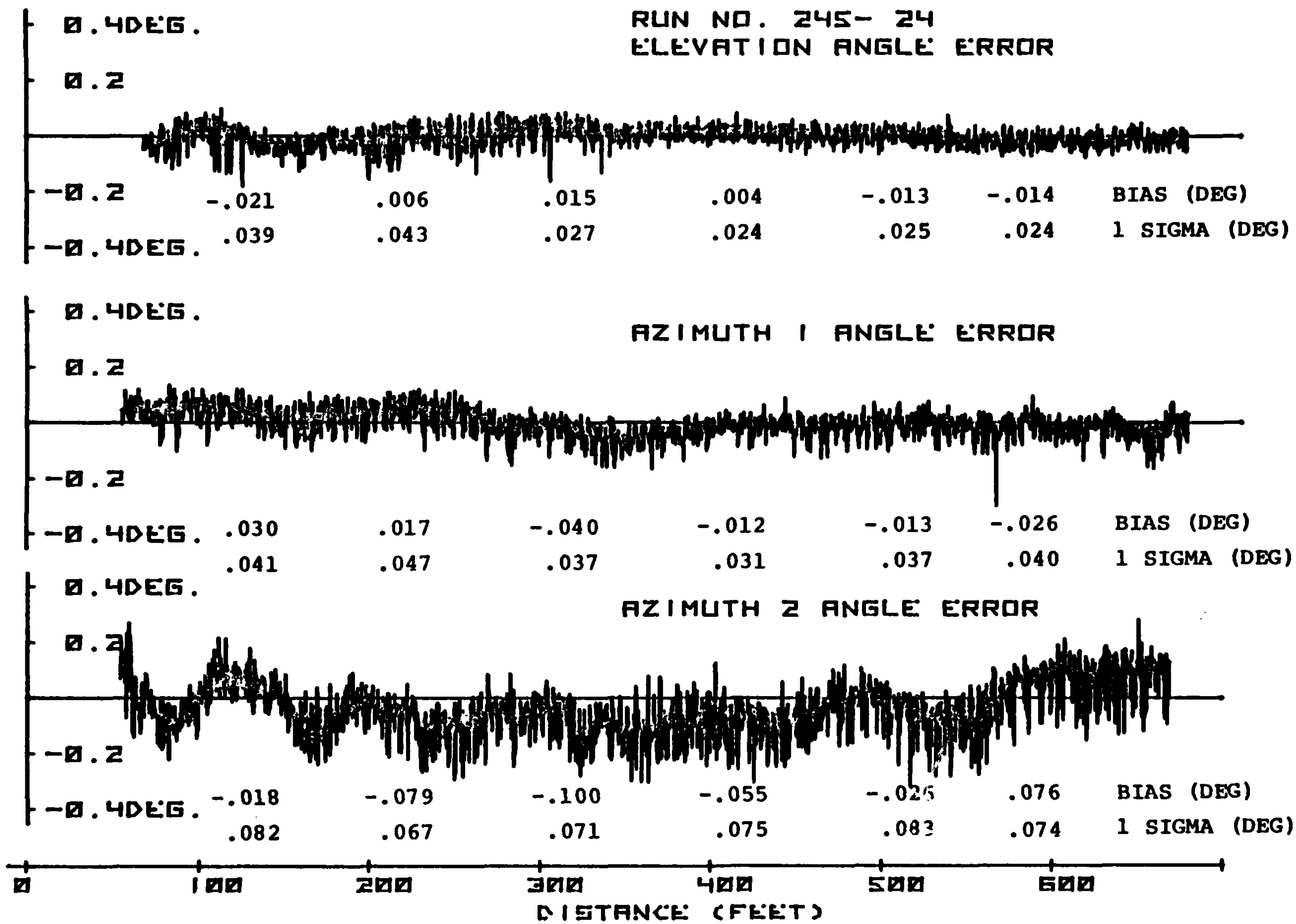


FIGURE 4-6A. 3° GLIDE SLOPE

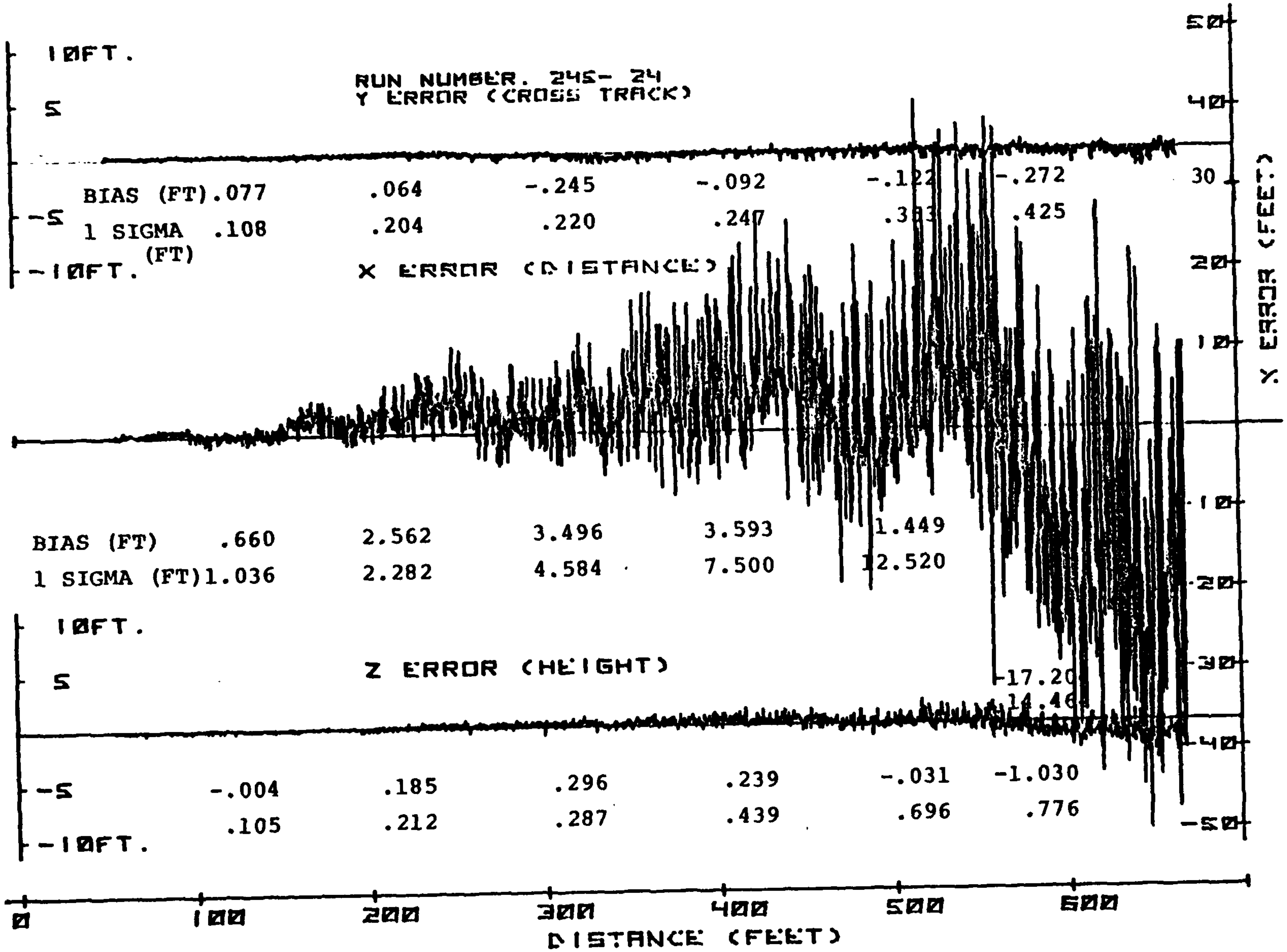


FIGURE 4-6B. 3° GLIDE SLOPE

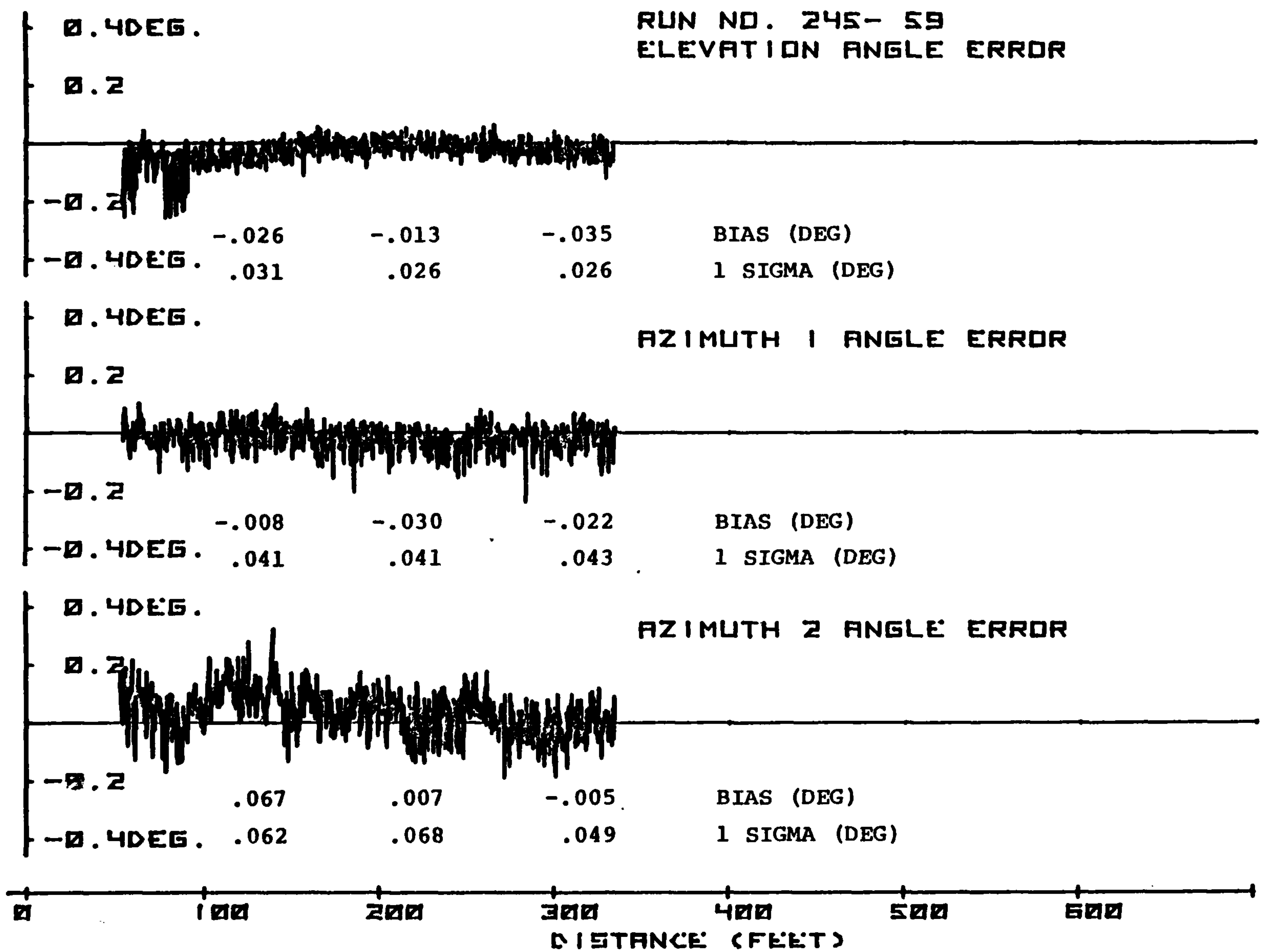


FIGURE 4-7A. 6° GLIDE SLOPE

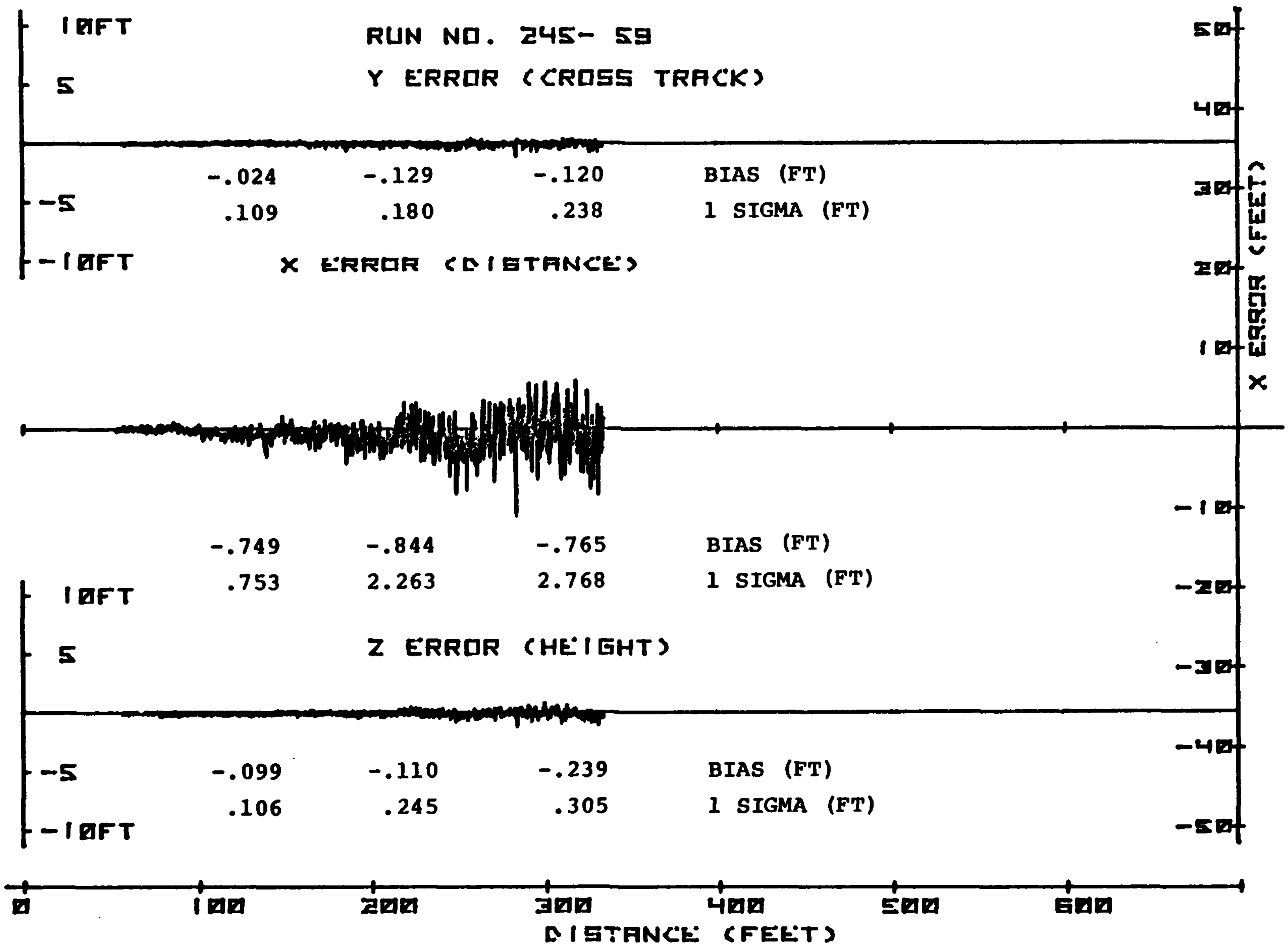


FIGURE 4-7B. 6° GLIDE SLOPE

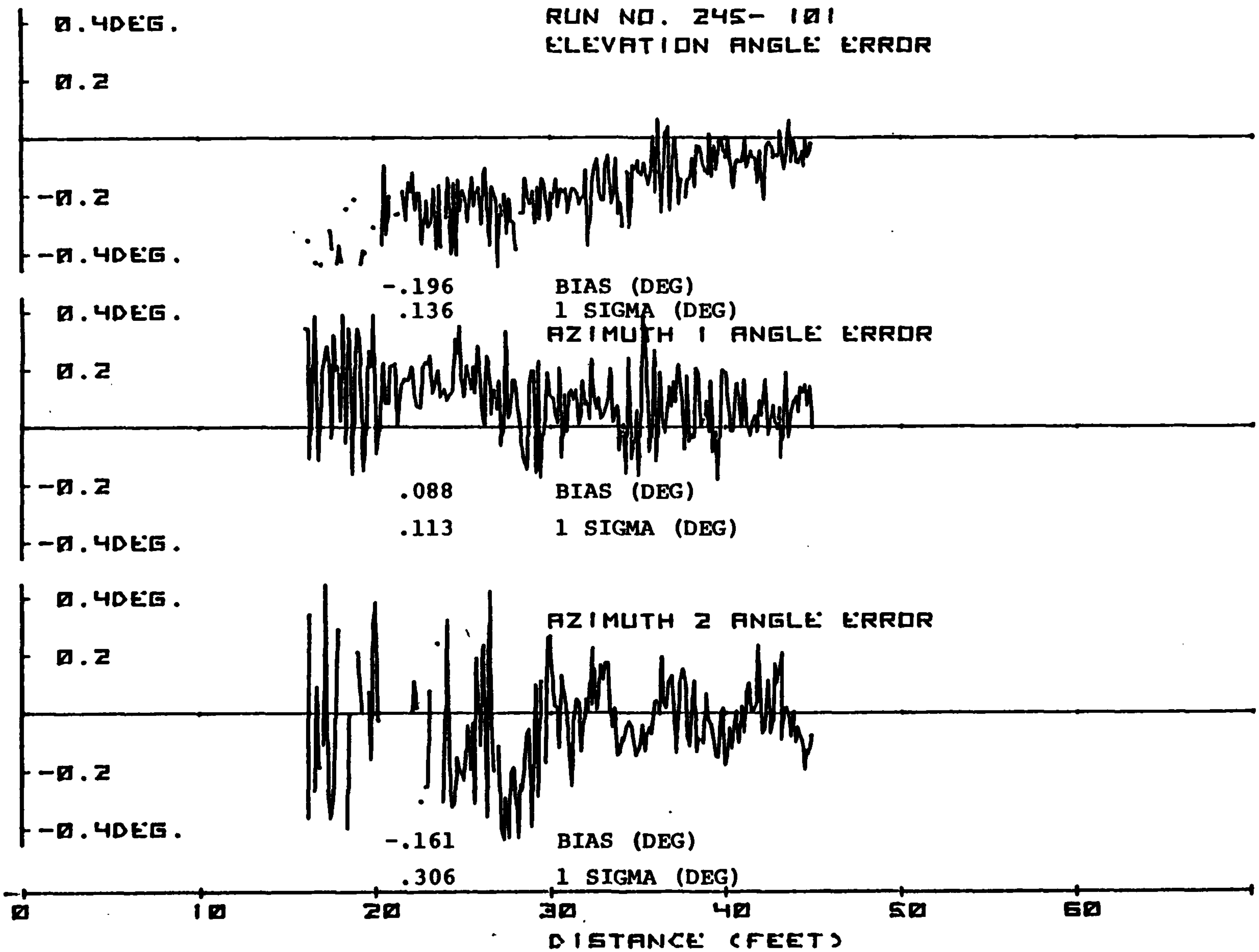


FIGURE 4-8A. 2' HEIGHT

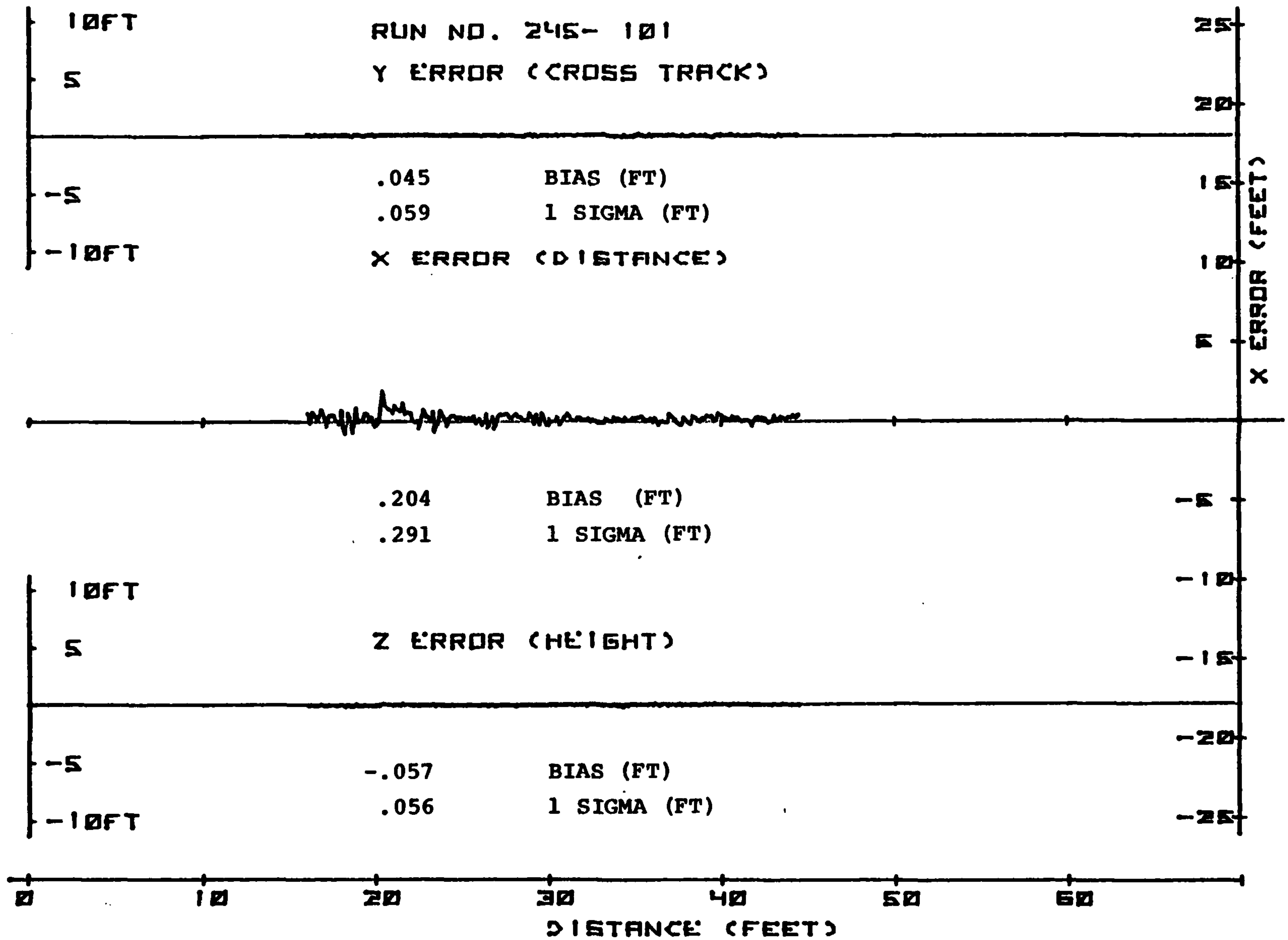


FIGURE 4-8B. 2' HEIGHT

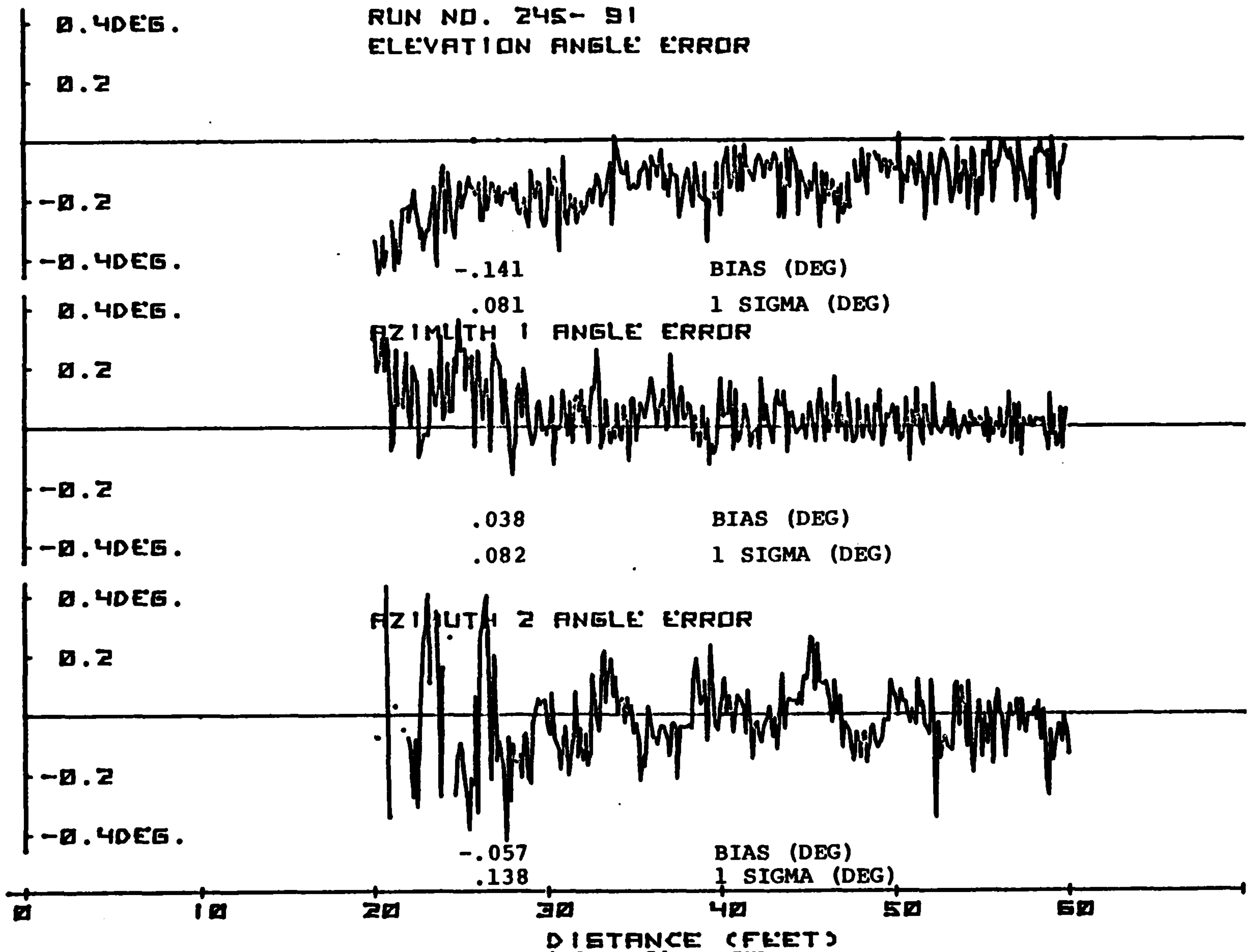


FIGURE 4-9A. 5' HEIGHT

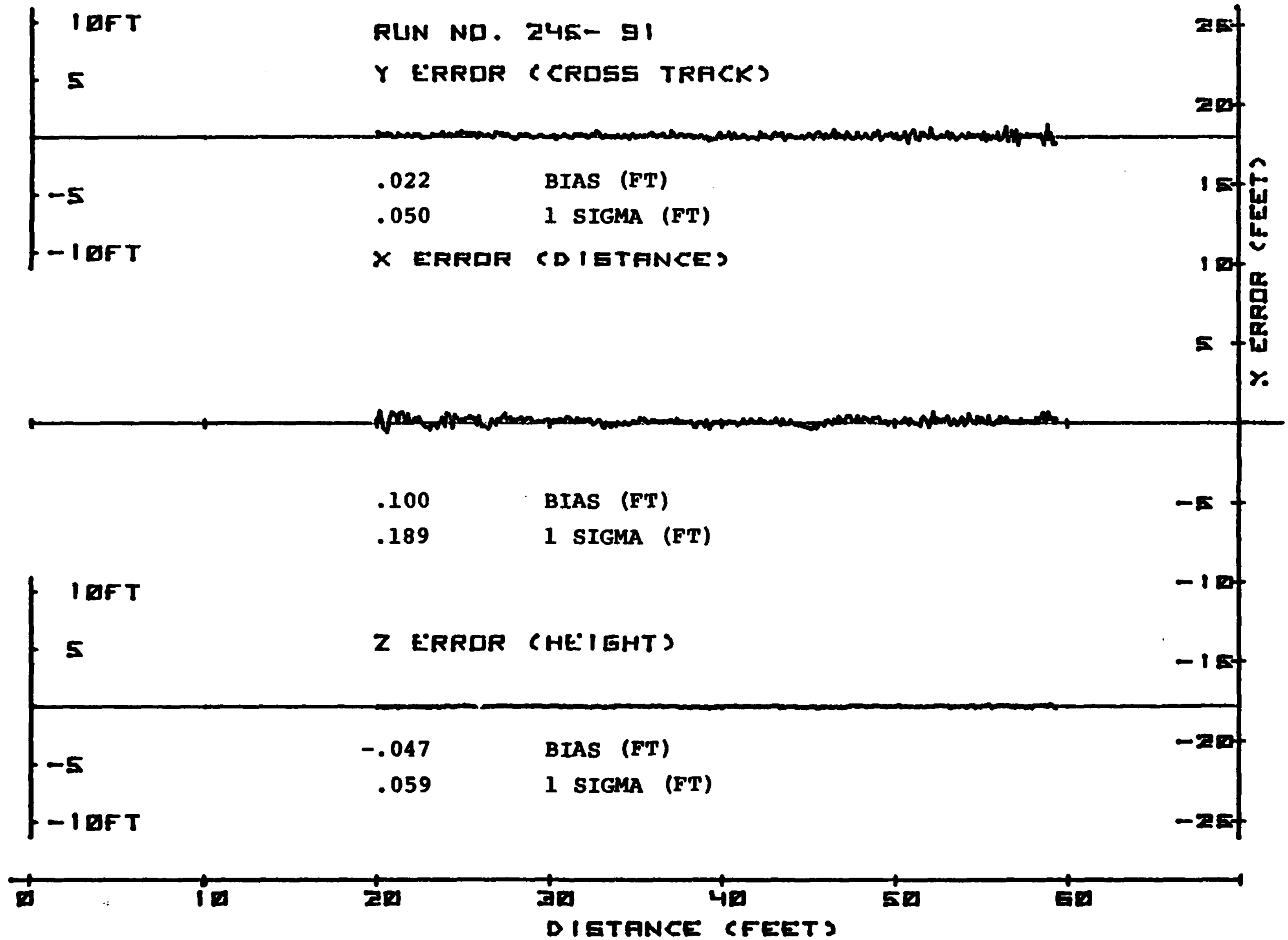


FIGURE 4-9B. 5' HEIGHT

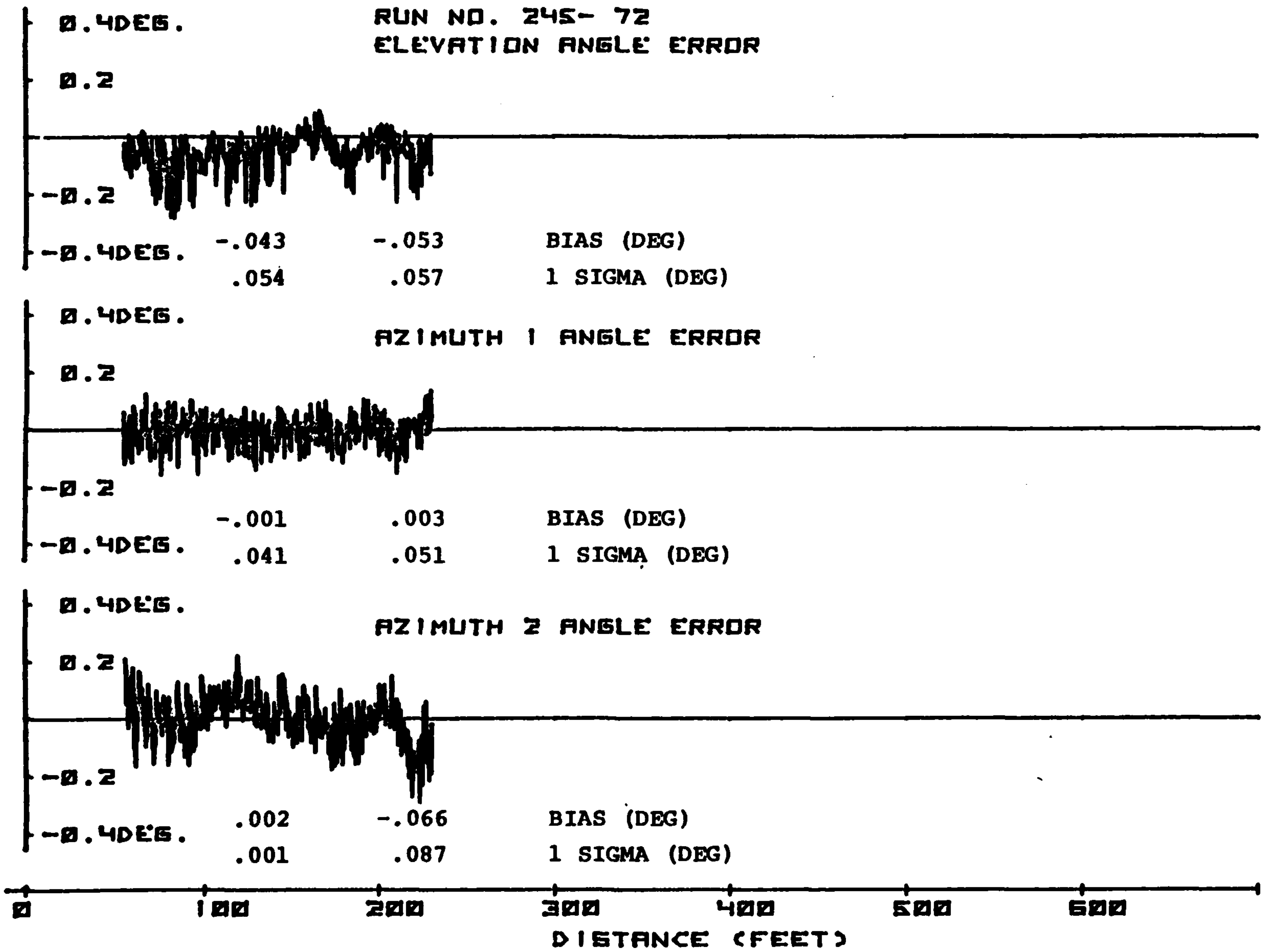


FIGURE 4-10A. 10' HEIGHT

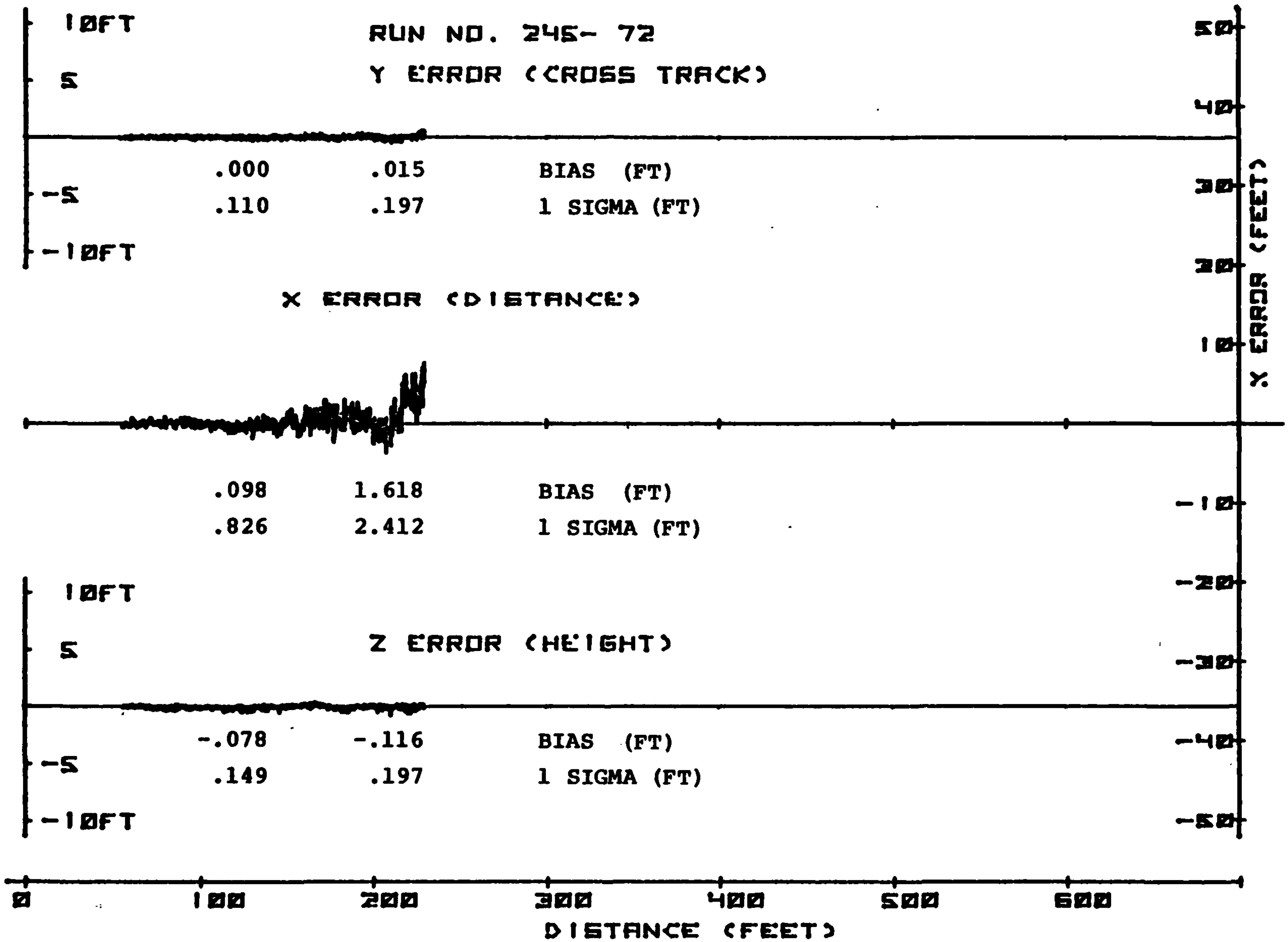


FIGURE 4-10B. 10' HEIGHT

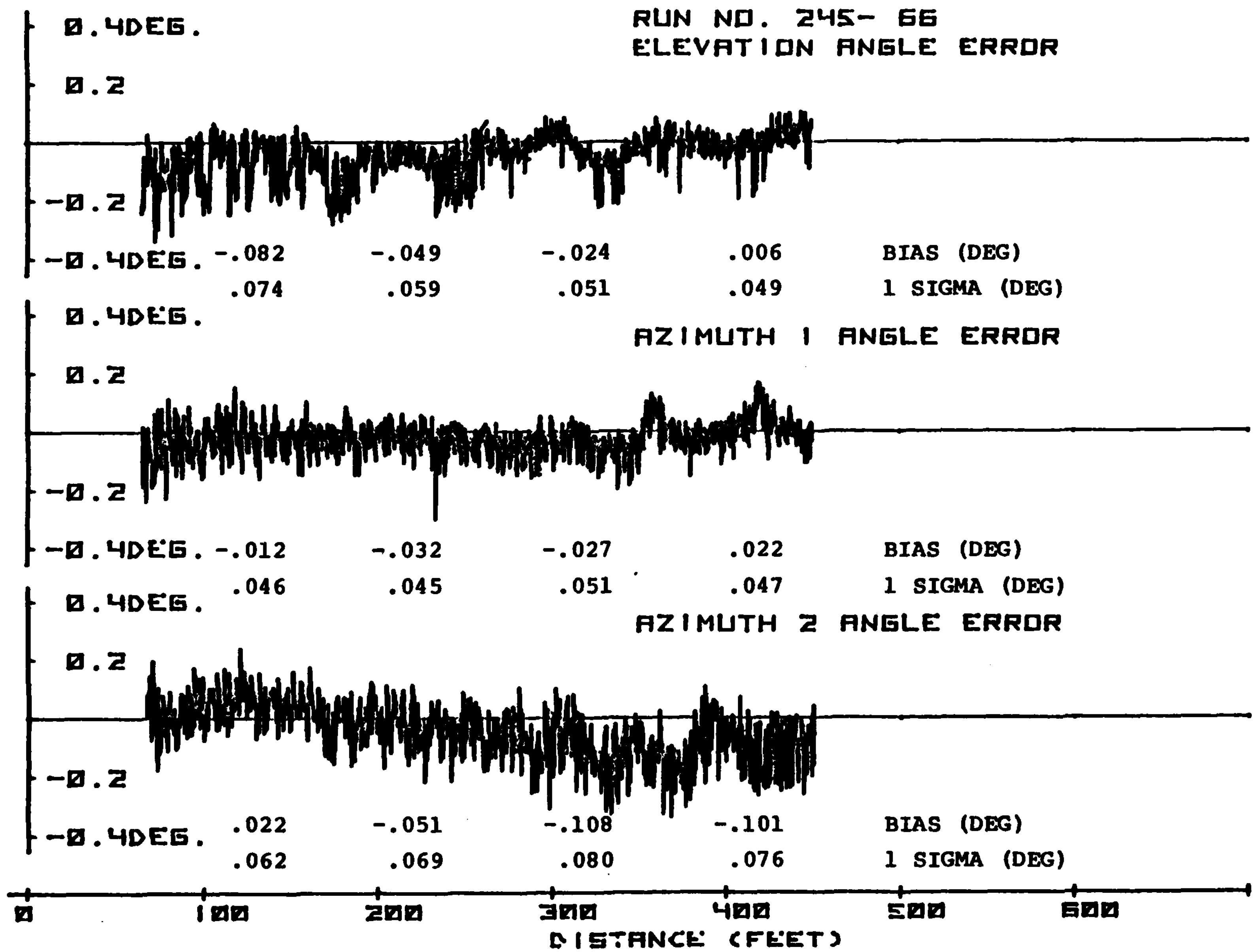


FIGURE 4-11A. 20' HEIGHT

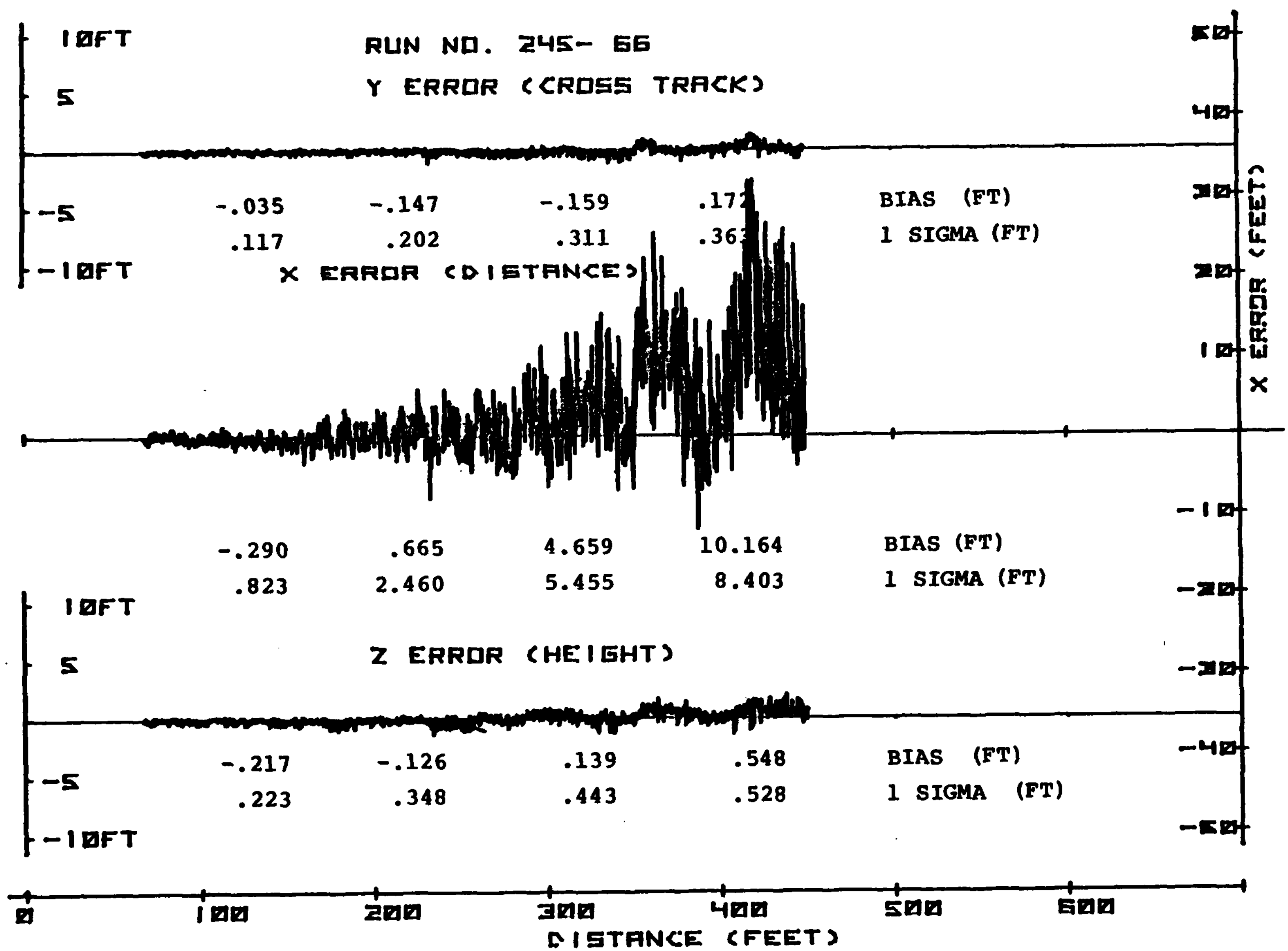


FIGURE 4-11B. 20' HEIGHT

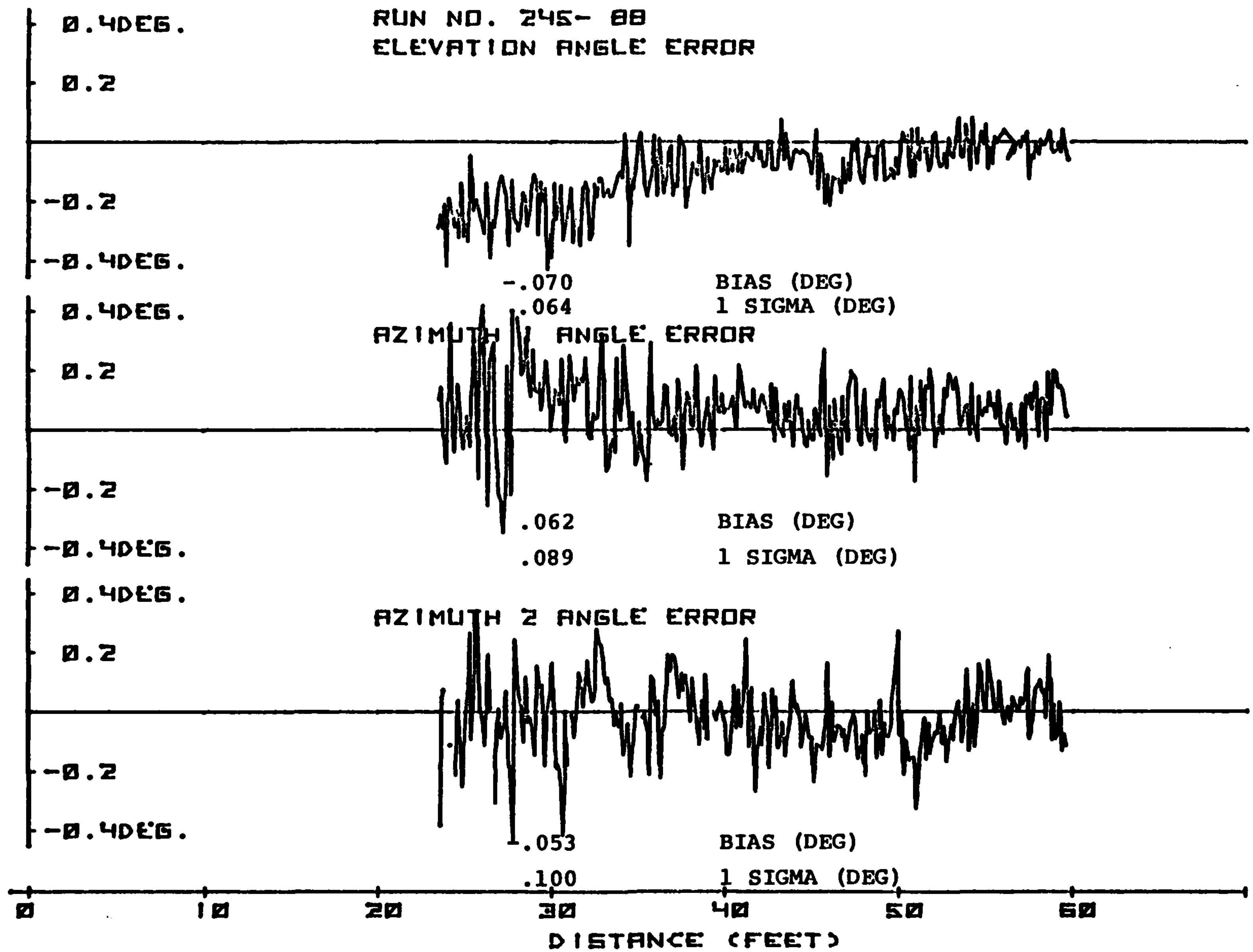


FIGURE 4-12A. 3° GLIDE SLOPE

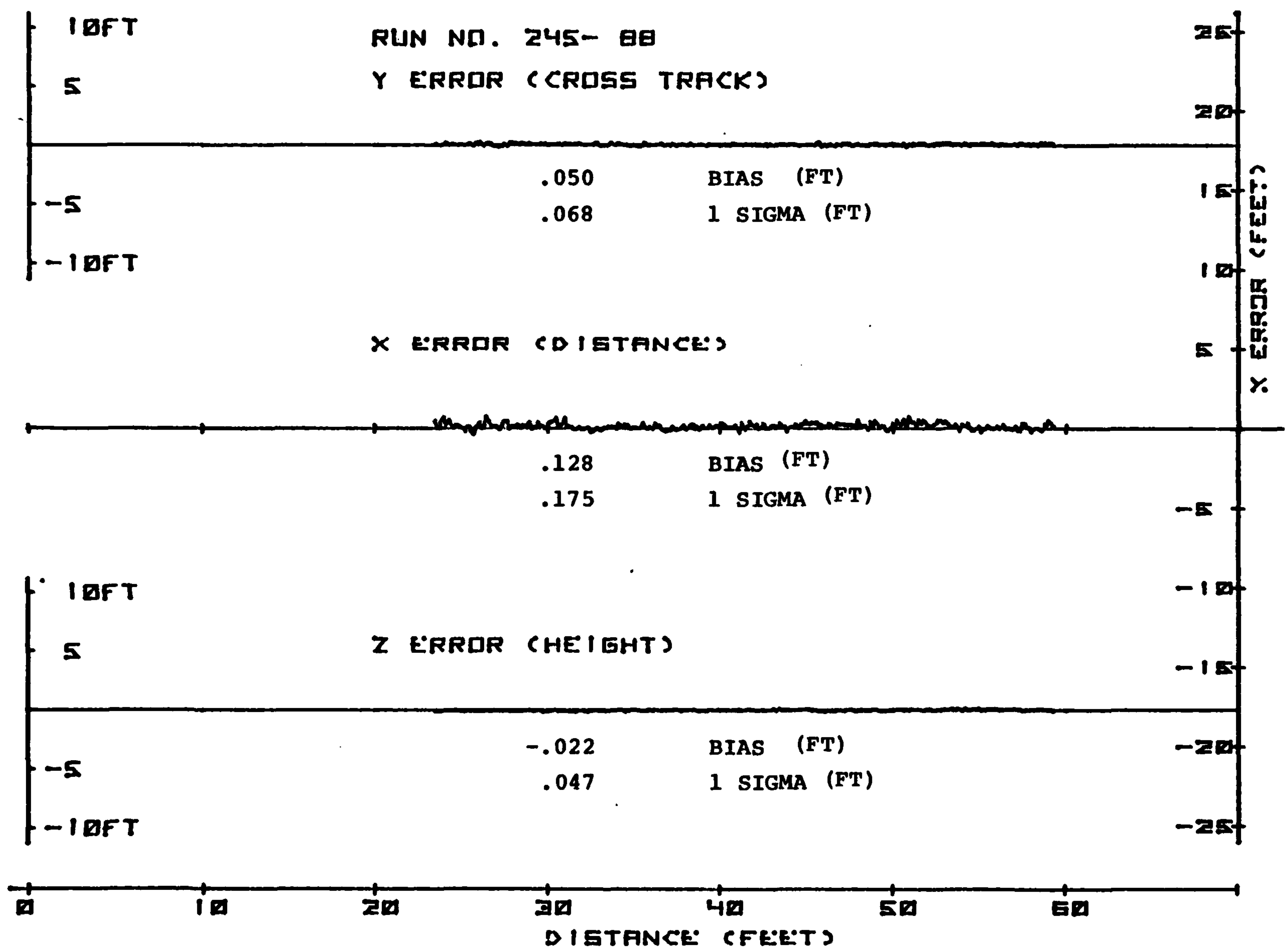


FIGURE 4-12B. 3° GLIDE SLOPE

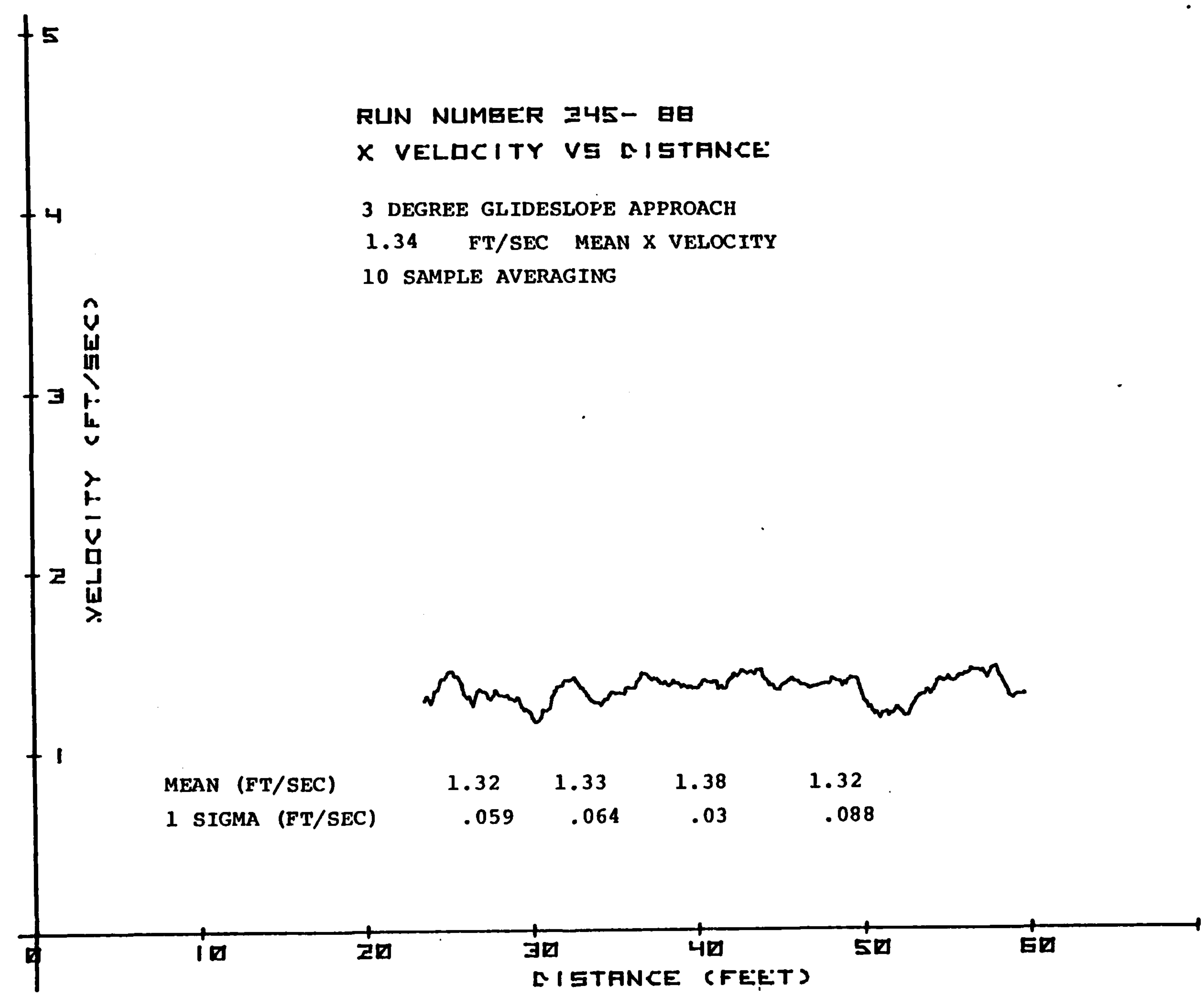


FIGURE 4-12C 3° GLIDE SLOPE

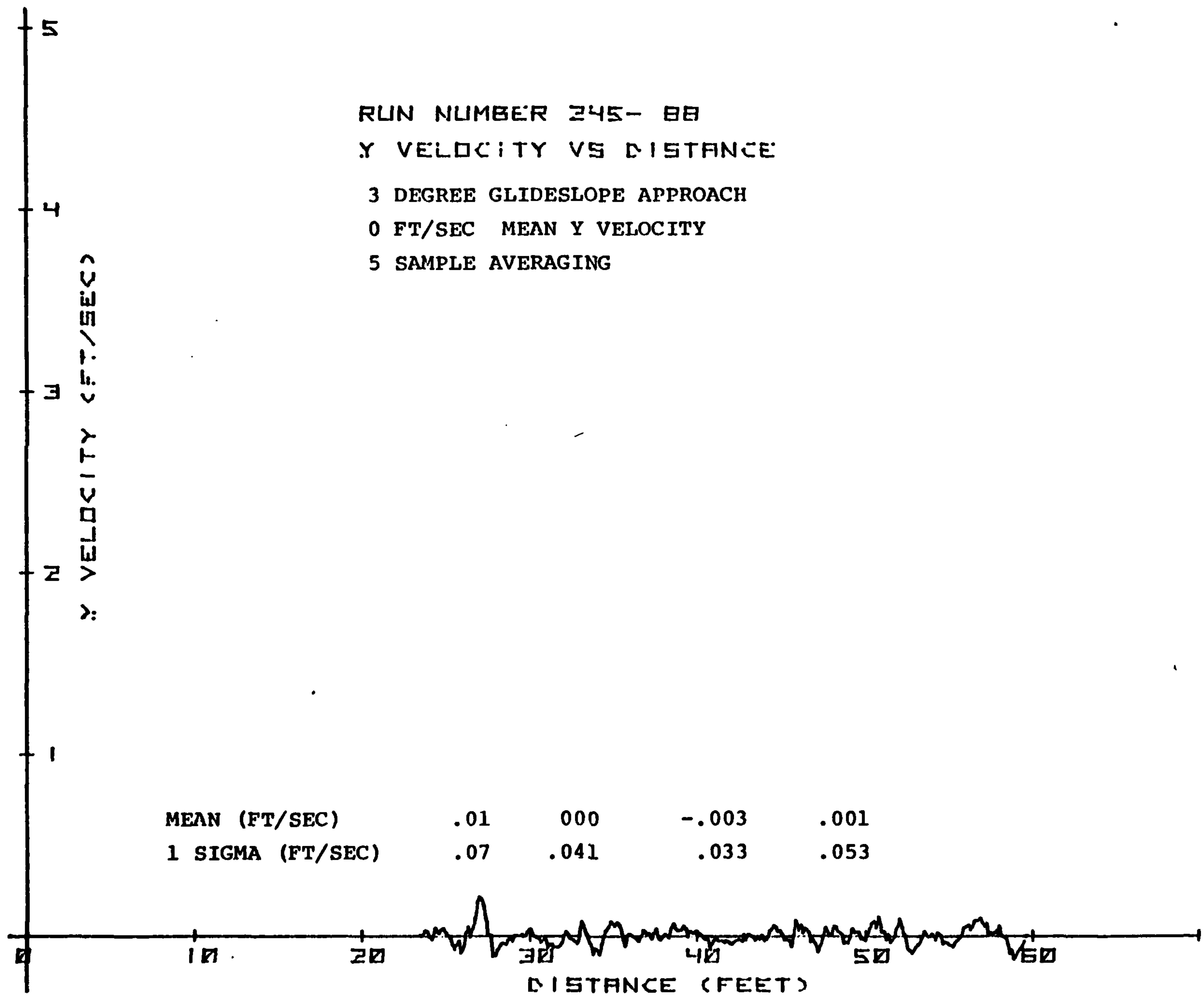


FIGURE 4-12D 3° GLIDE SLOPE

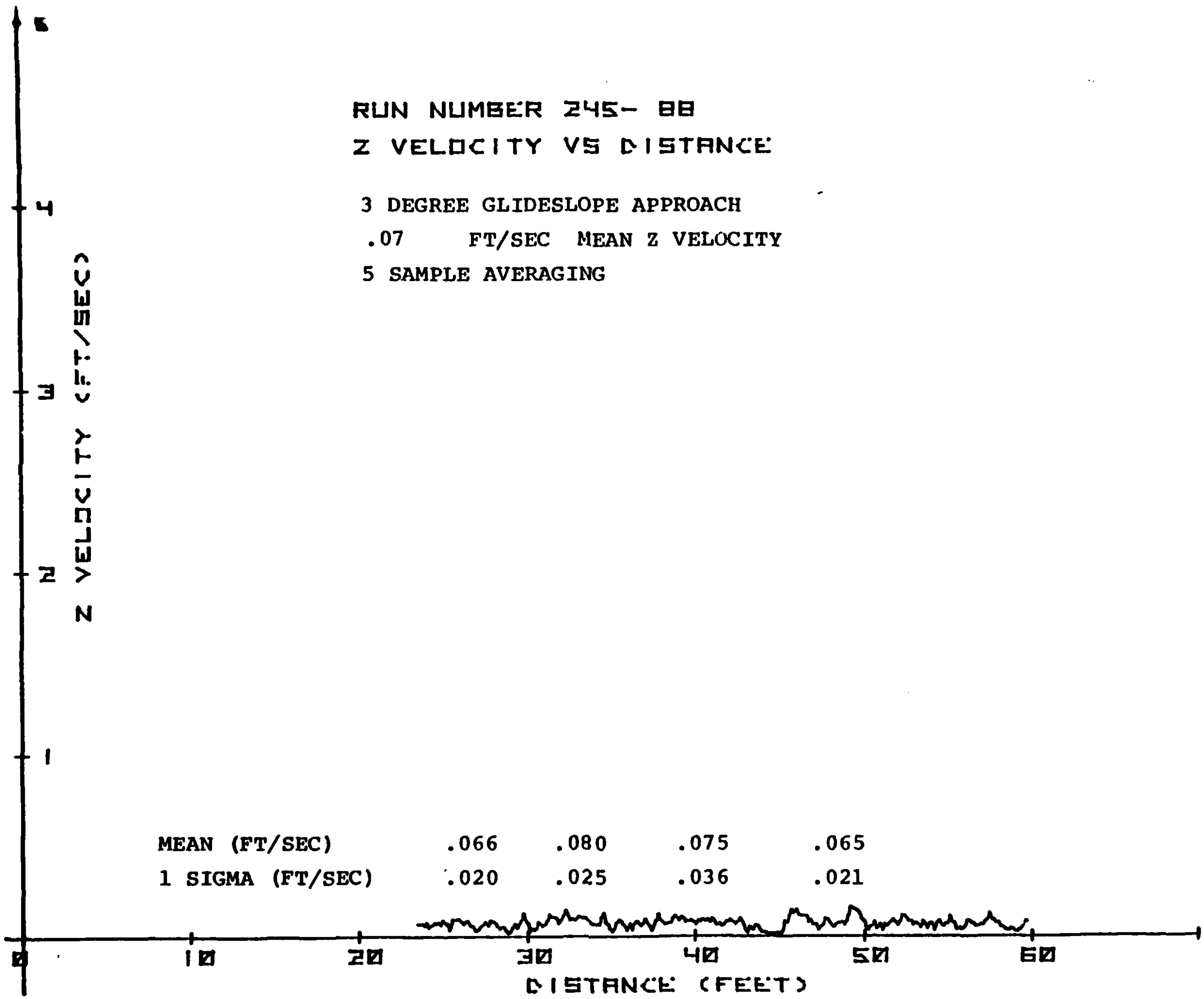


FIGURE 4-12E 3° GLIDE SLOPE

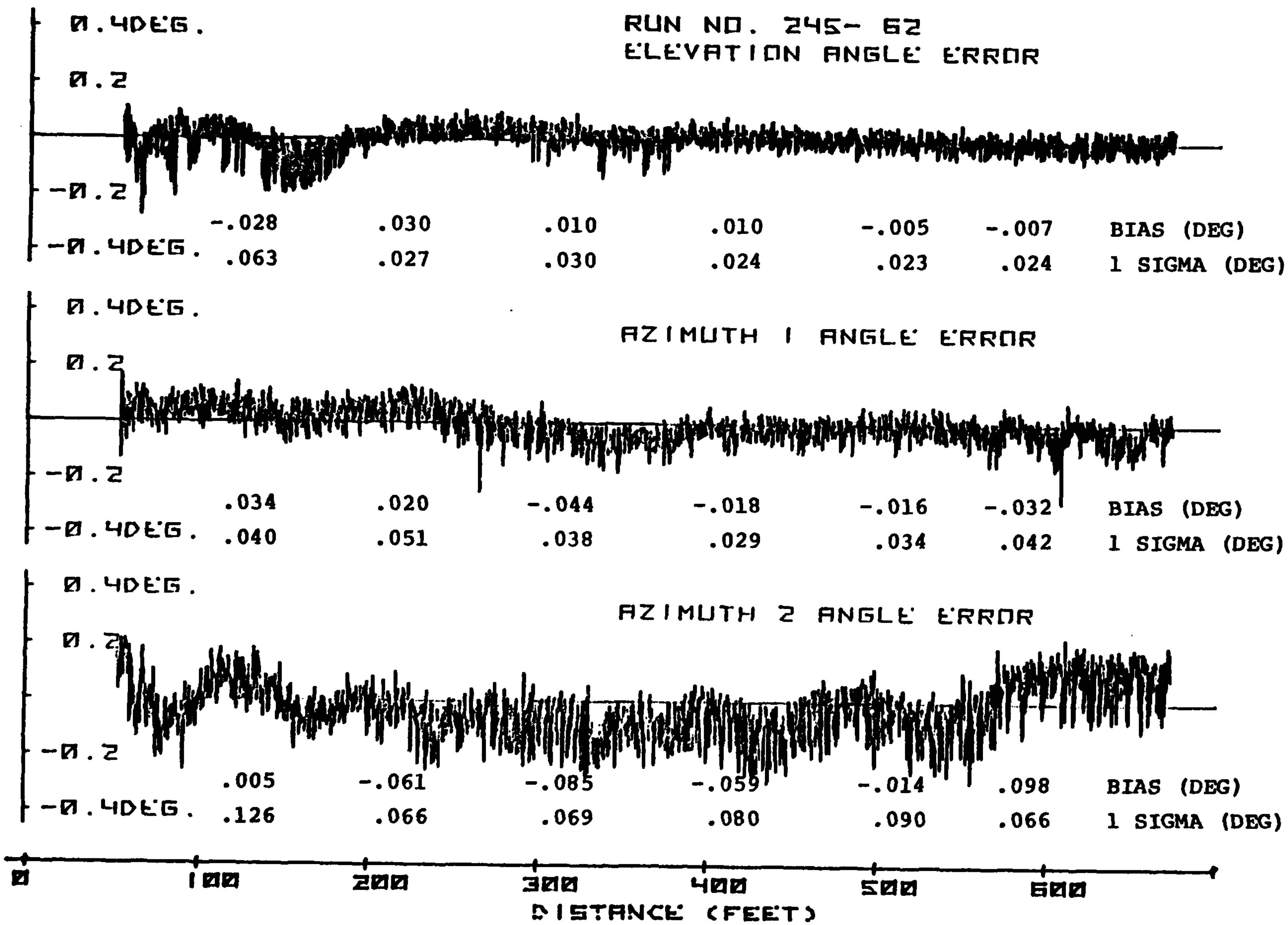


FIGURE 4-13A. 3° GLIDE SLOPE

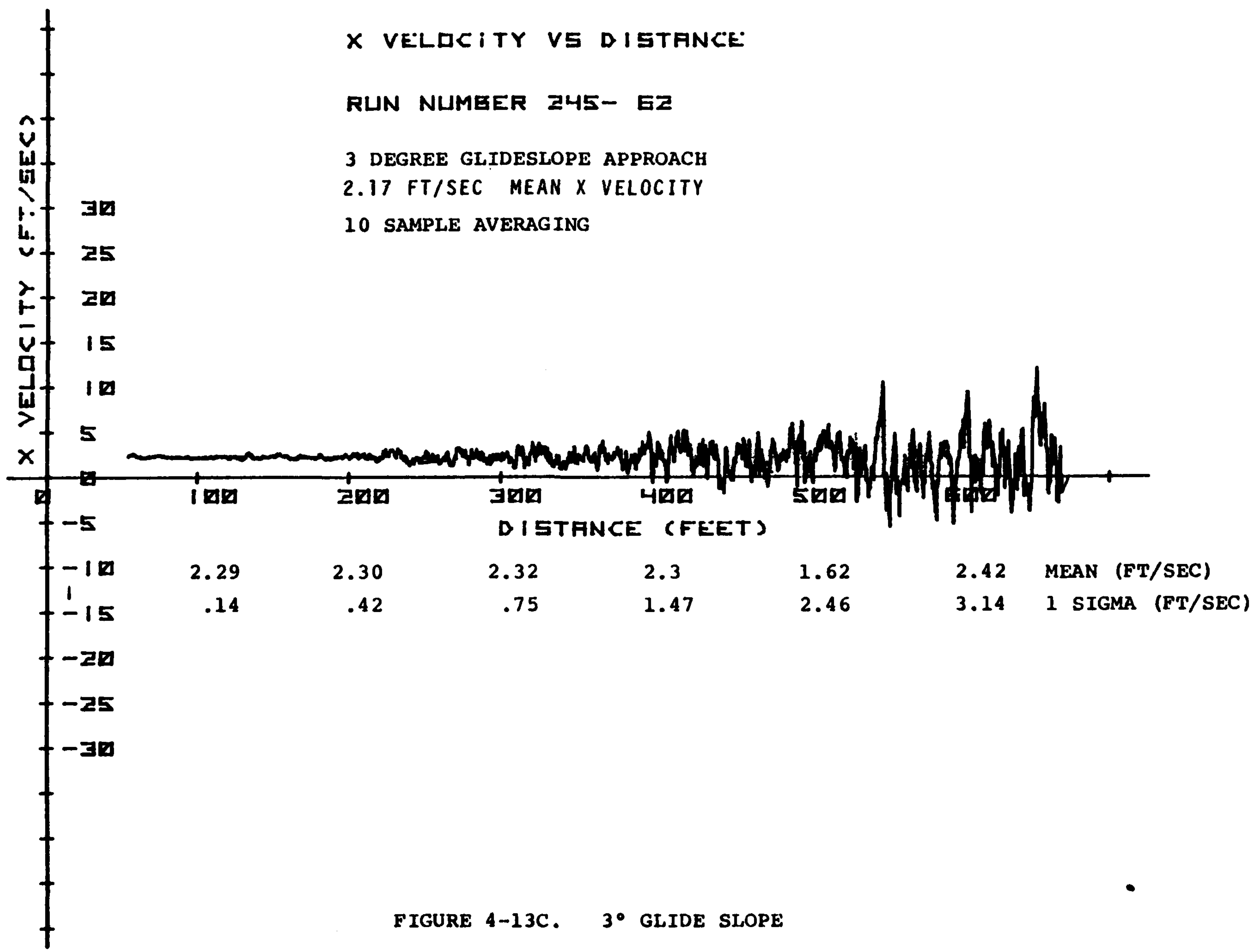


FIGURE 4-13C. 3° GLIDE SLOPE

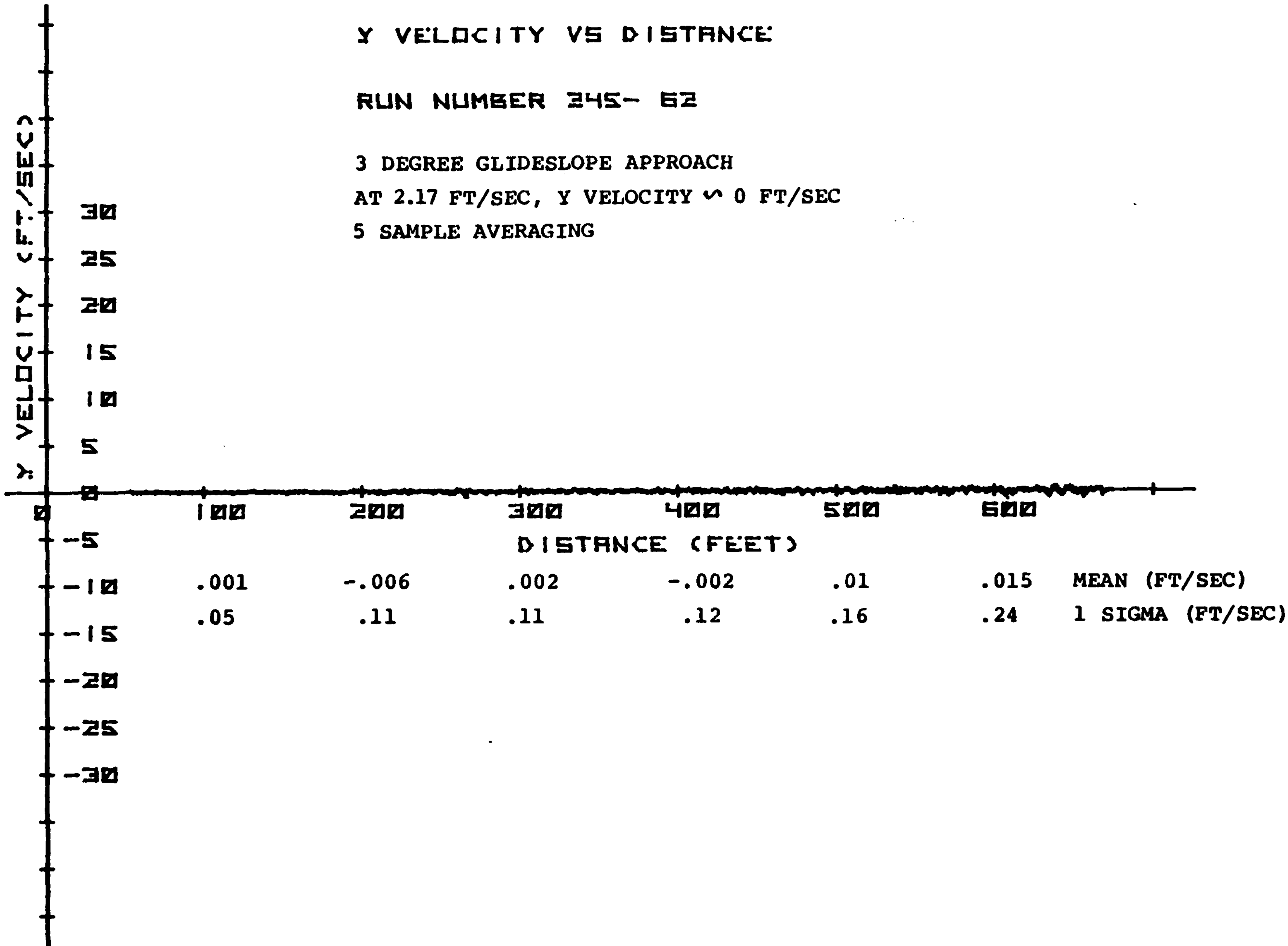
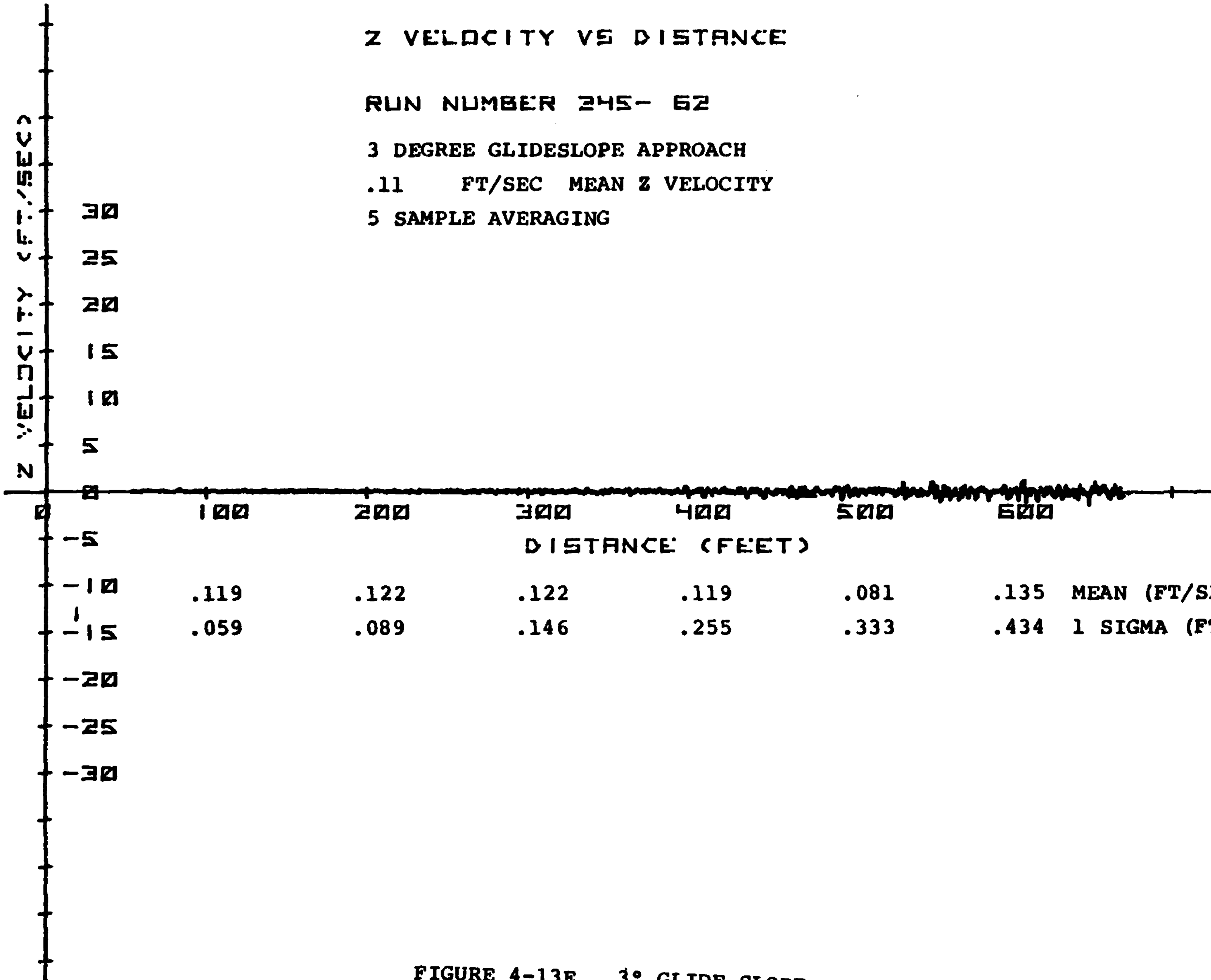


FIGURE 4-13D 3° GLIDE SLOPE



.119	.122	.122	.119	.081	.135	MEAN (FT/SEC)
.059	.089	.146	.255	.333	.434	1 SIGMA (FT/SEC)

FIGURE 4-13E 3° GLIDE SLOPE

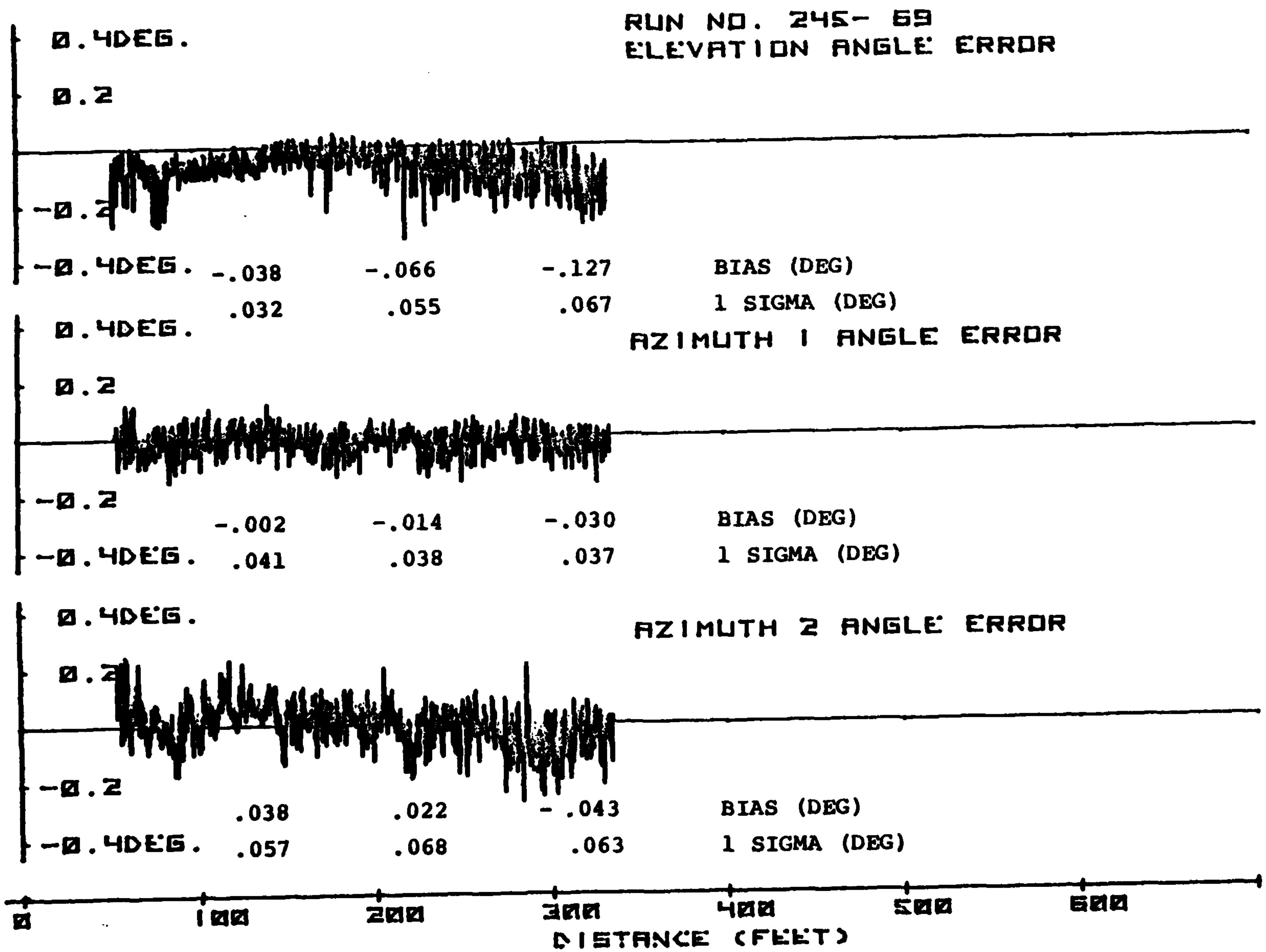


FIGURE 4-14A. 6° GLIDE SLOPE

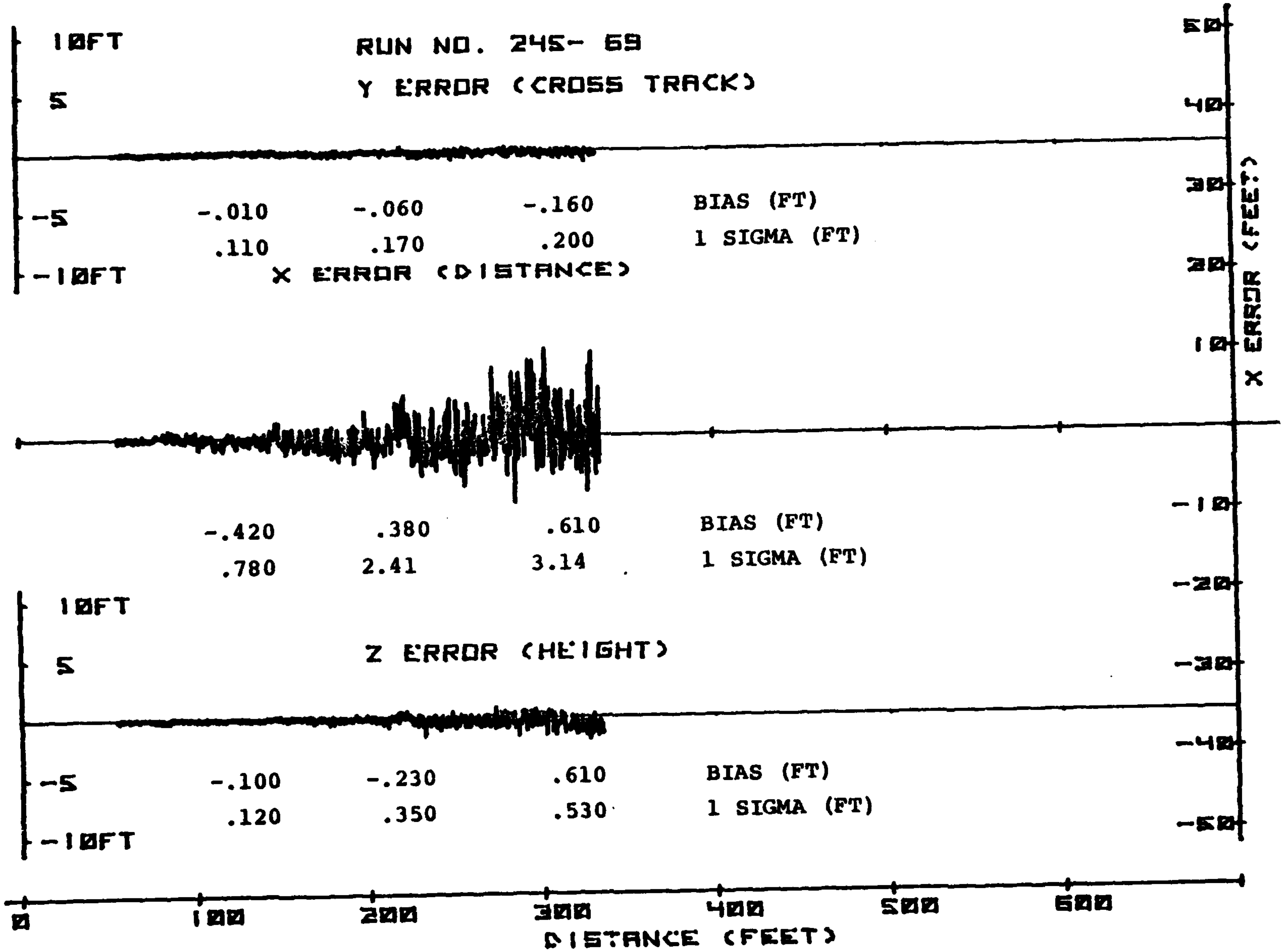


FIGURE 4-14B. 6° GLIDE SLOPE

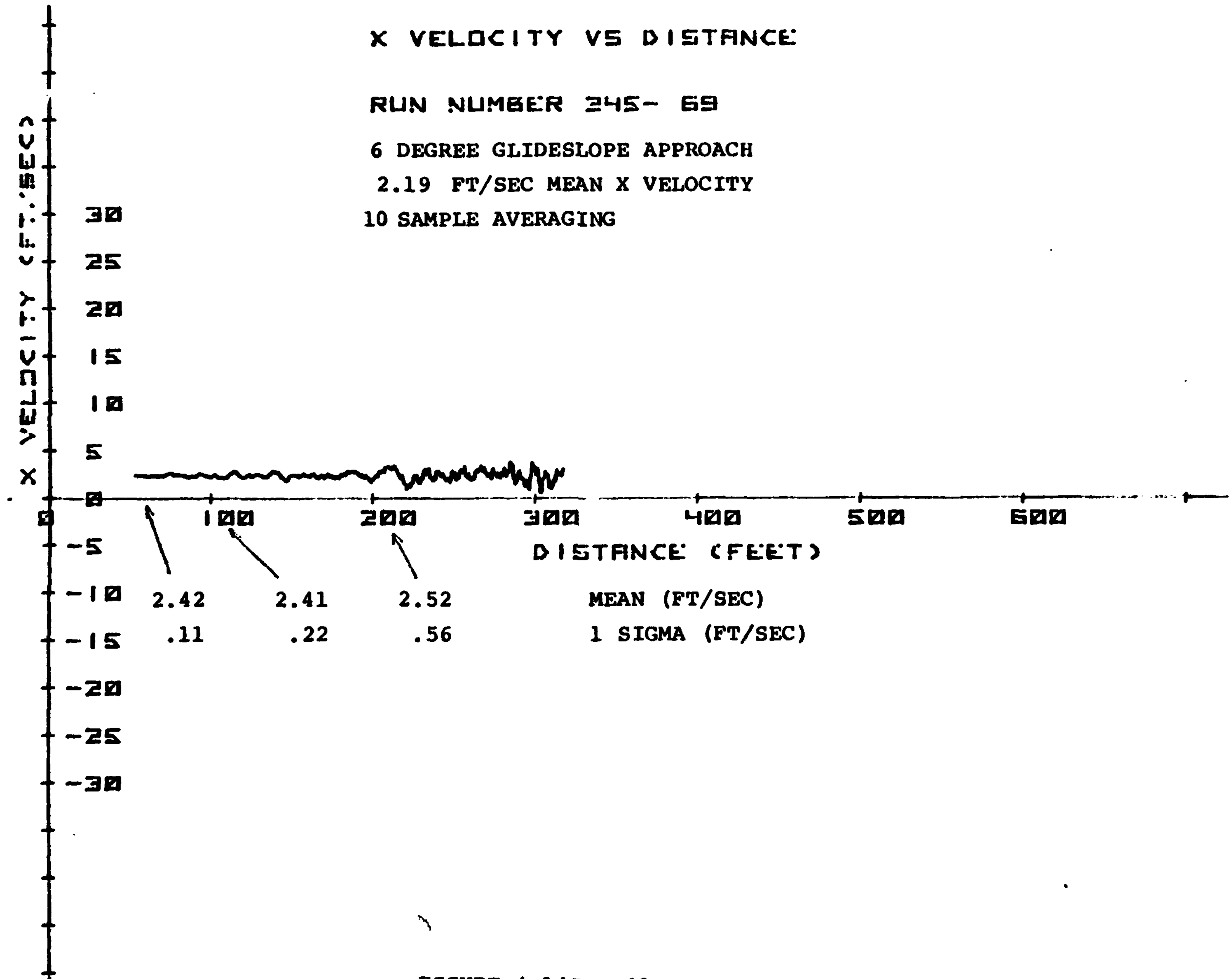


FIGURE 4-14C 6° GLIDE SLOPE

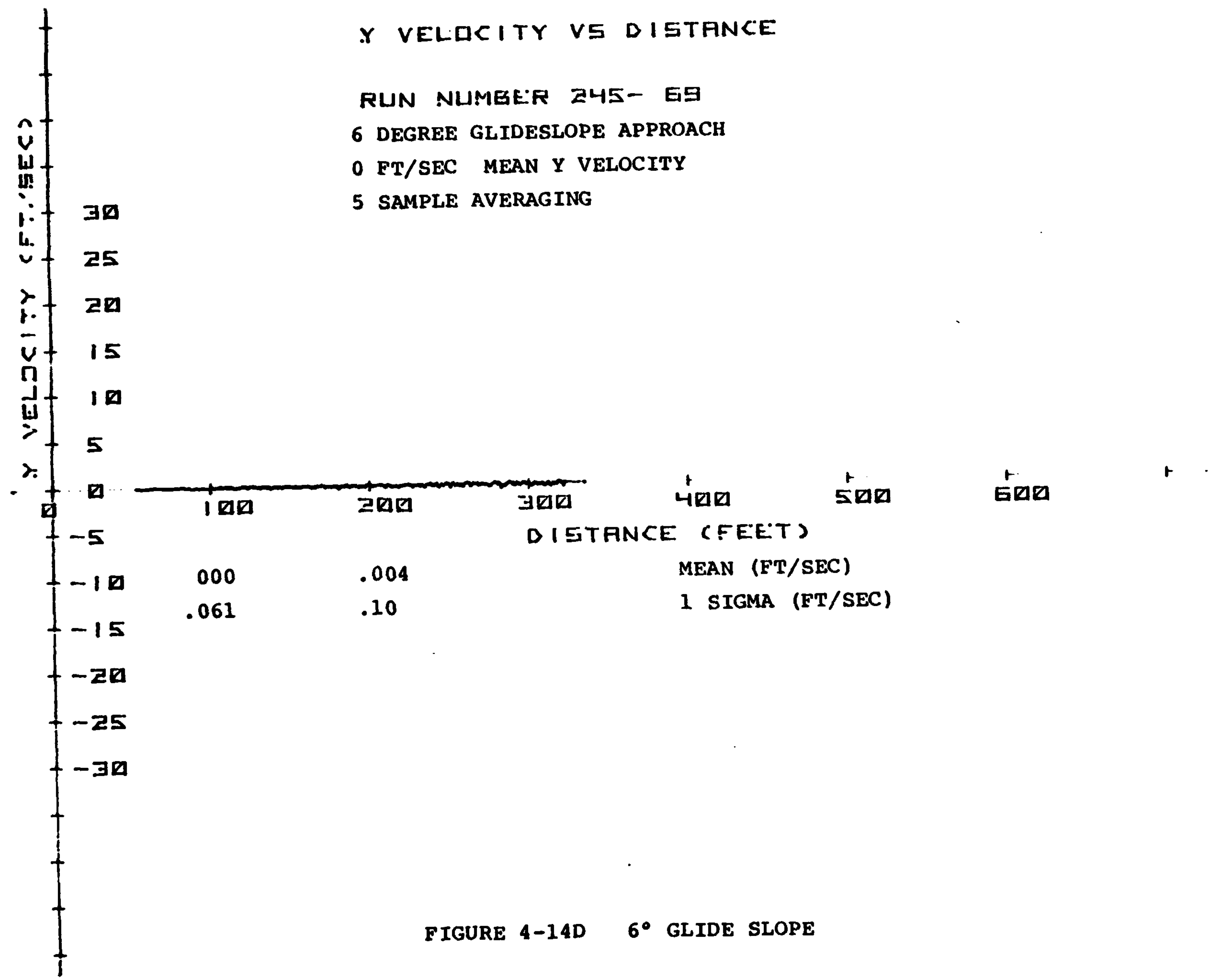


FIGURE 4-14D 6° GLIDE SLOPE

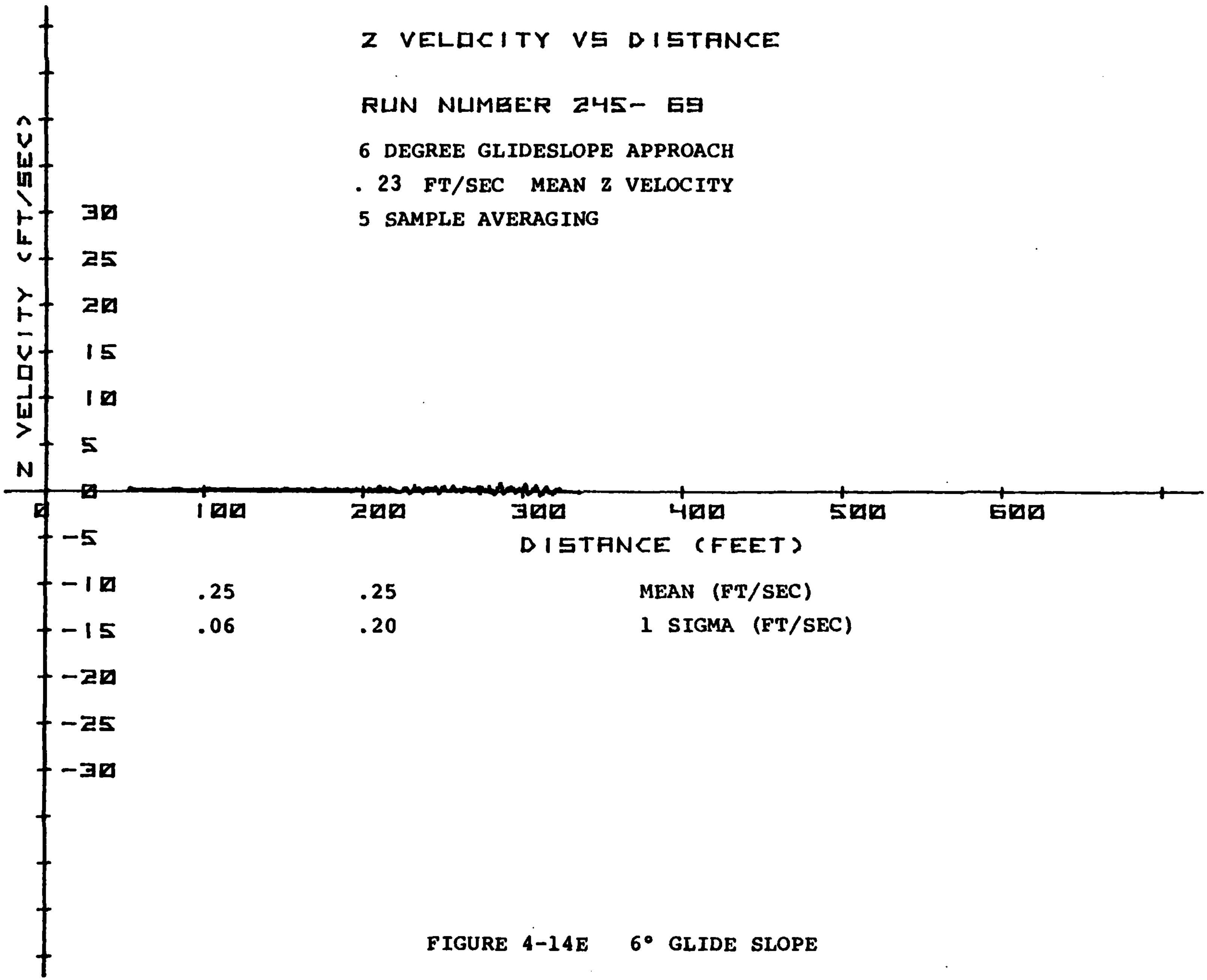


FIGURE 4-14E 6° GLIDE SLOPE

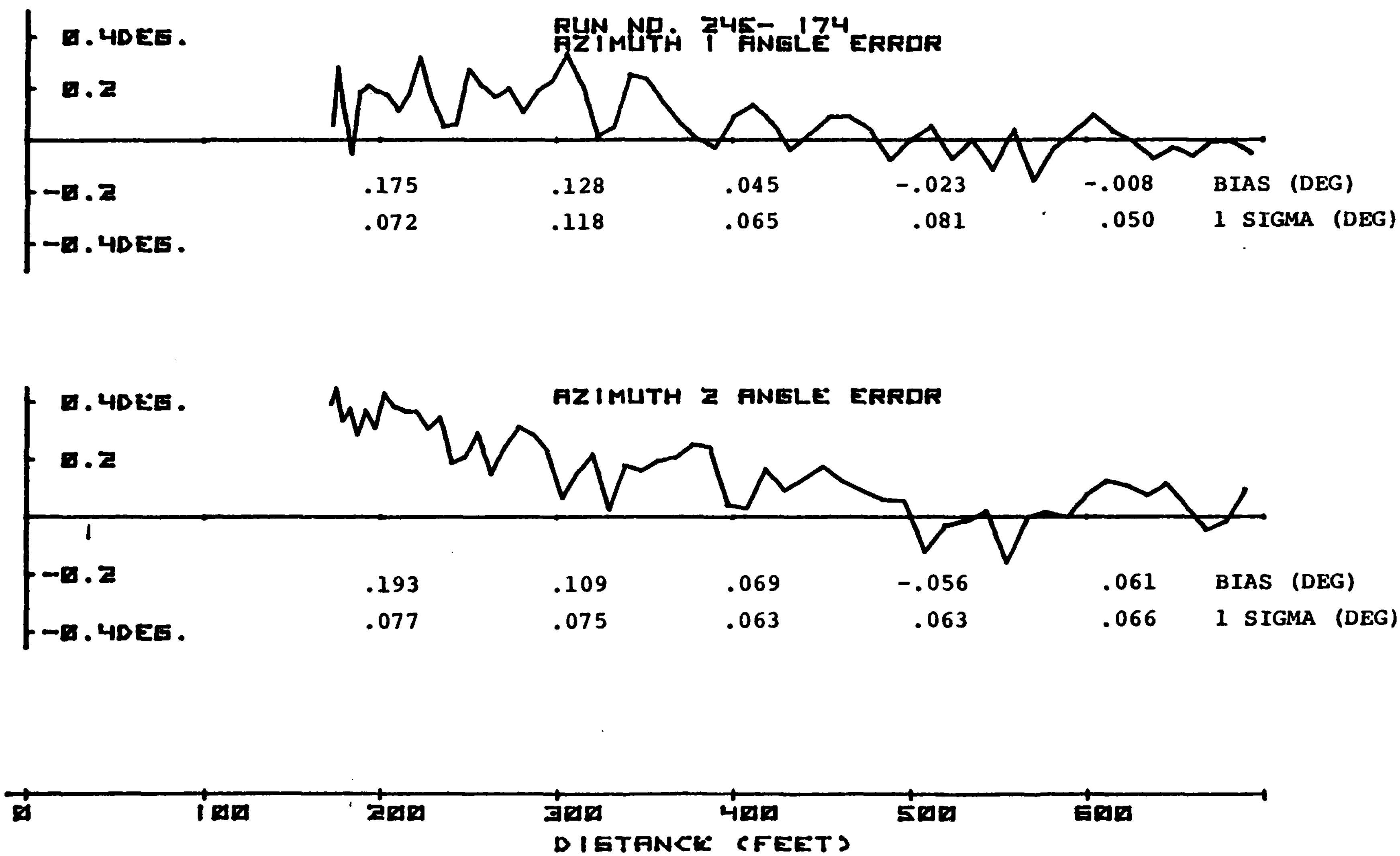


FIGURE 4-15A. 30 MPH TRUCK TEST - 15' HEIGHT

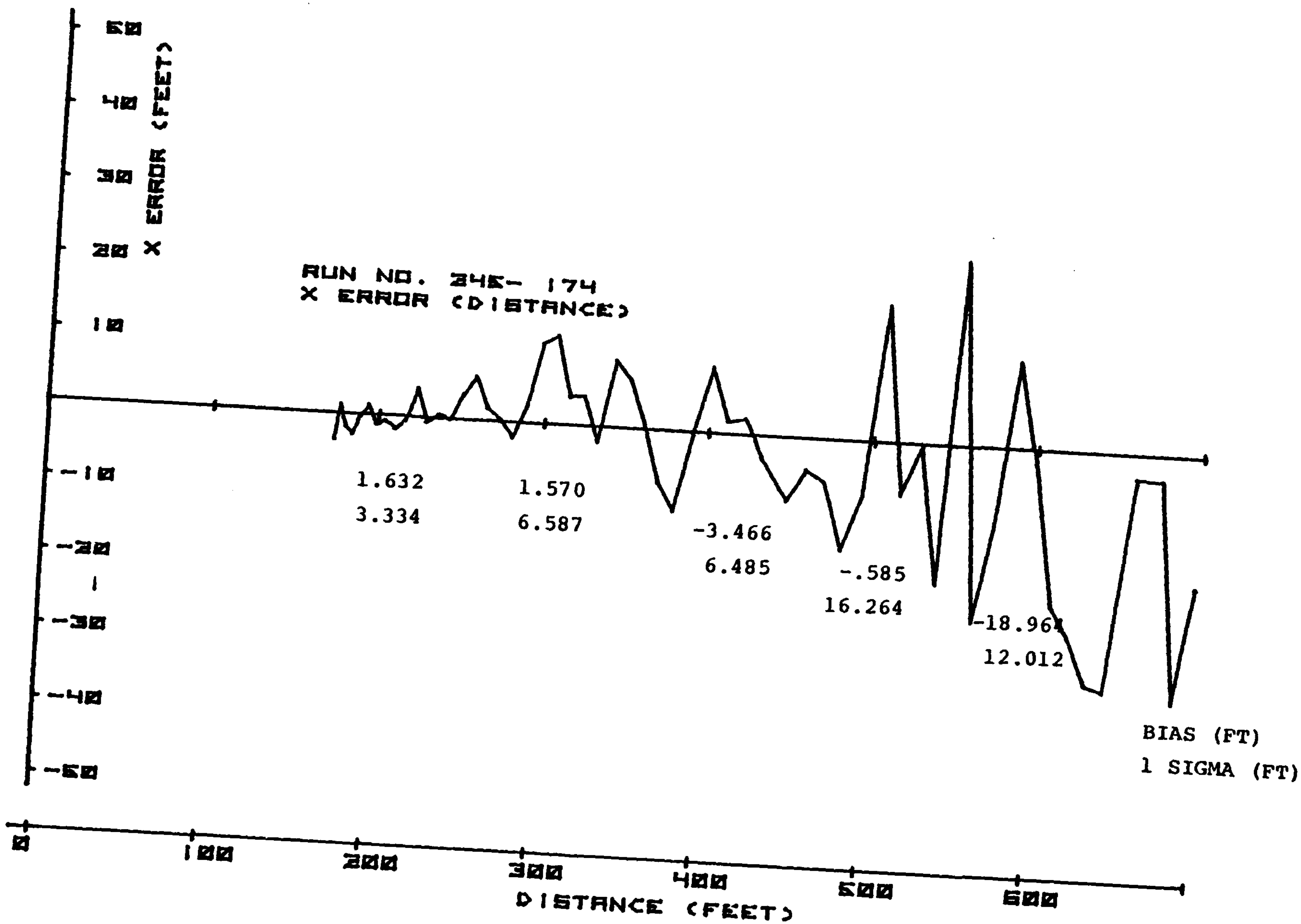


FIGURE 4-15B. 30 MPH TRUCK TEST - 15' HEIGHT

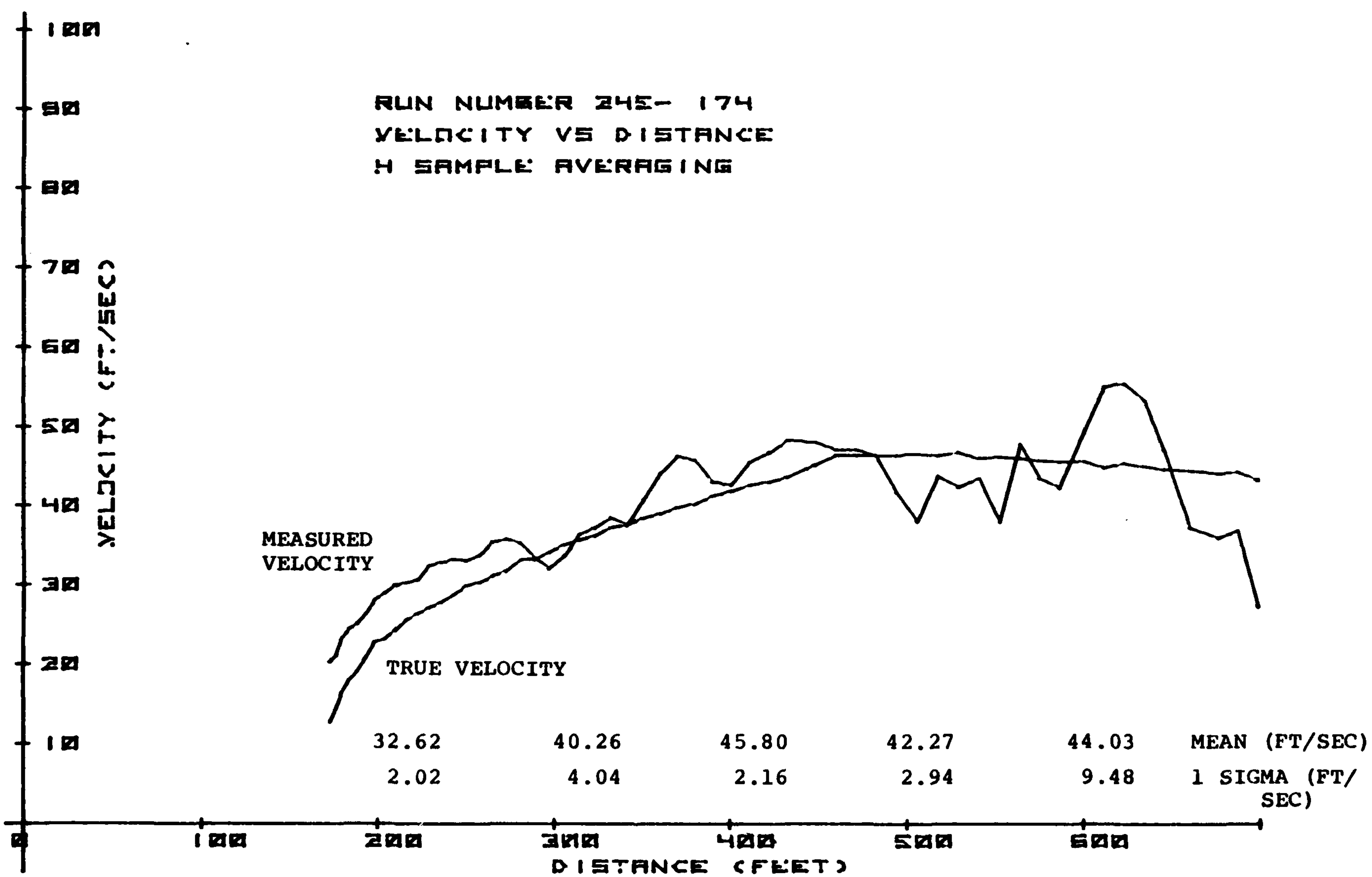


FIGURE 4-15C. 30 MPH TRUCK TEST - 15' HEIGHT

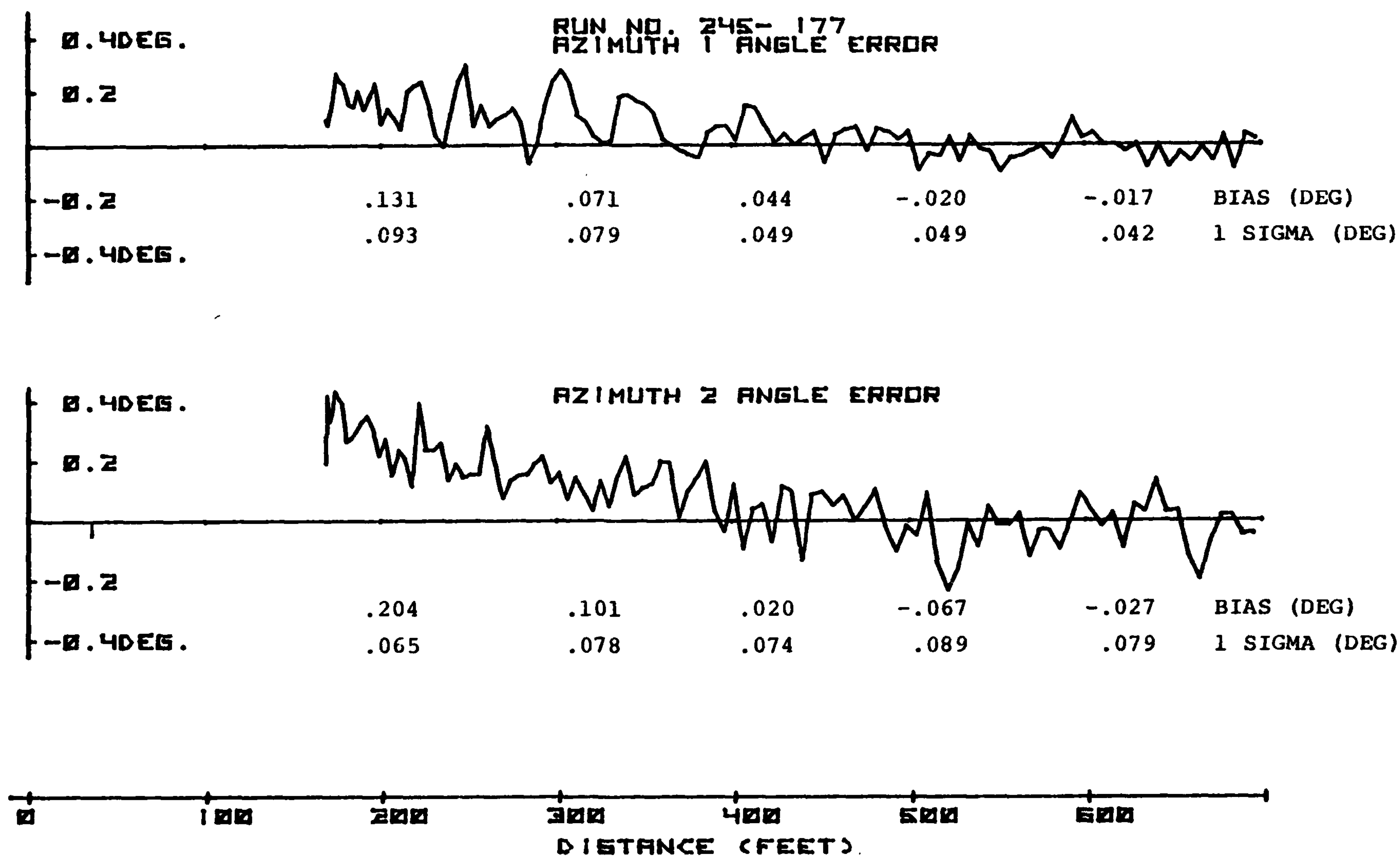


FIGURE 4-16A. 15 MPH TRUCK TEST - 15' HEIGHT

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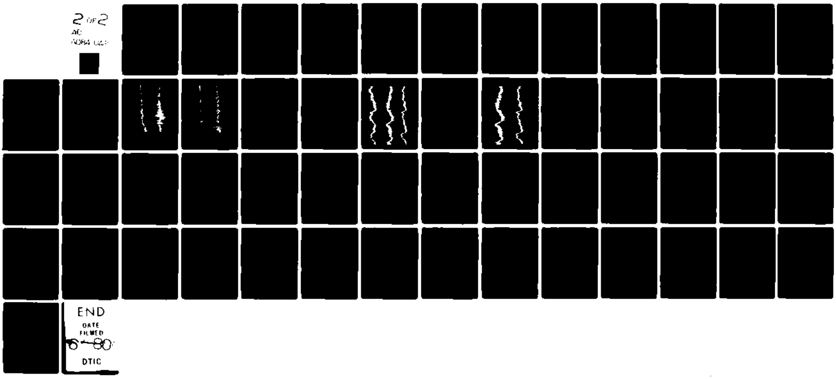

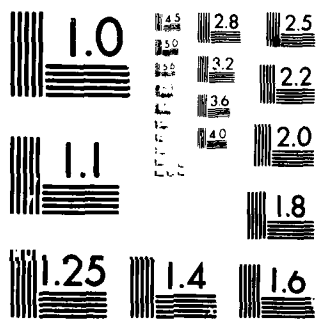

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

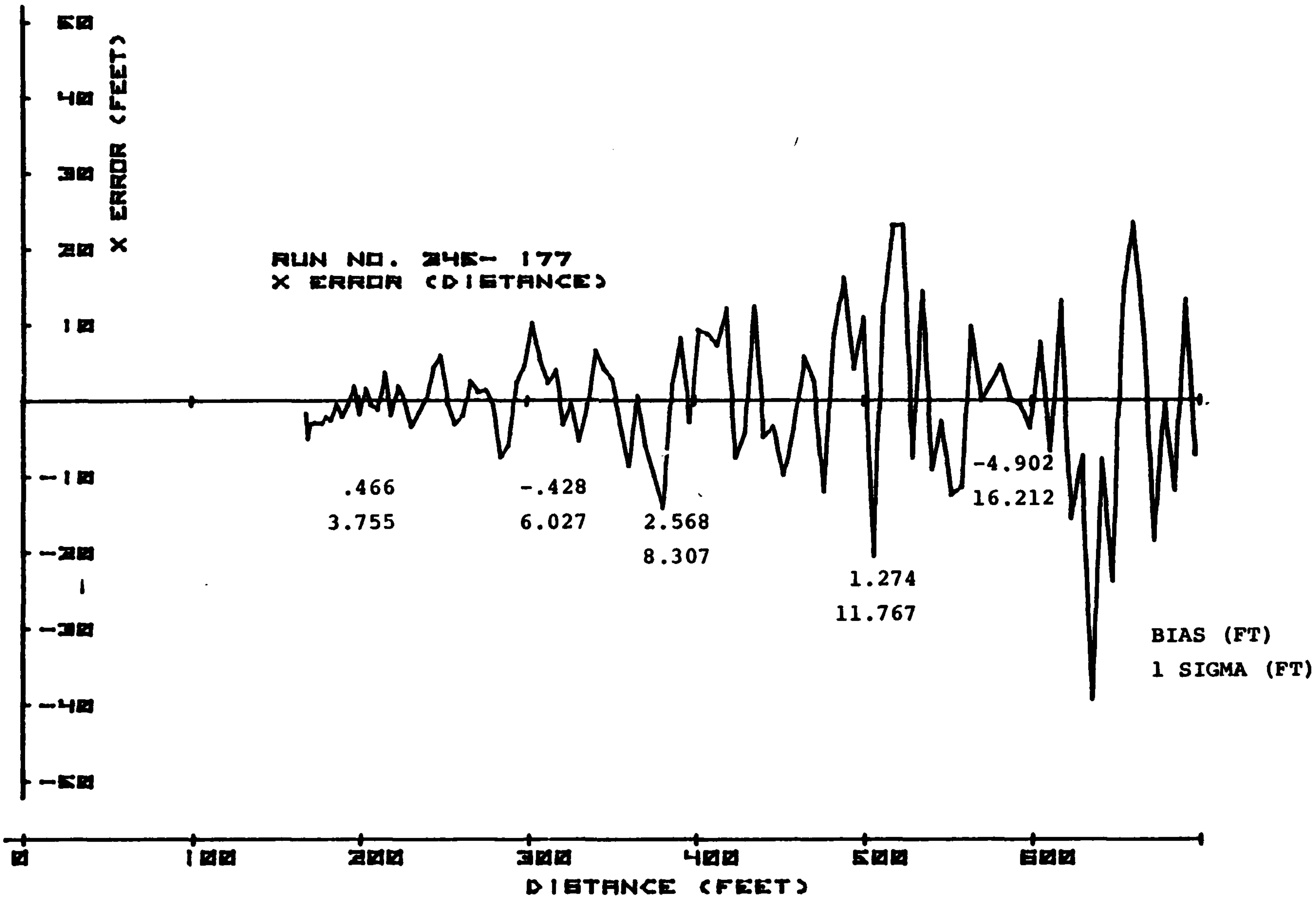

FIGURE 4-16B. 15 MPH TRUCK TEST - 15' HEIGHT

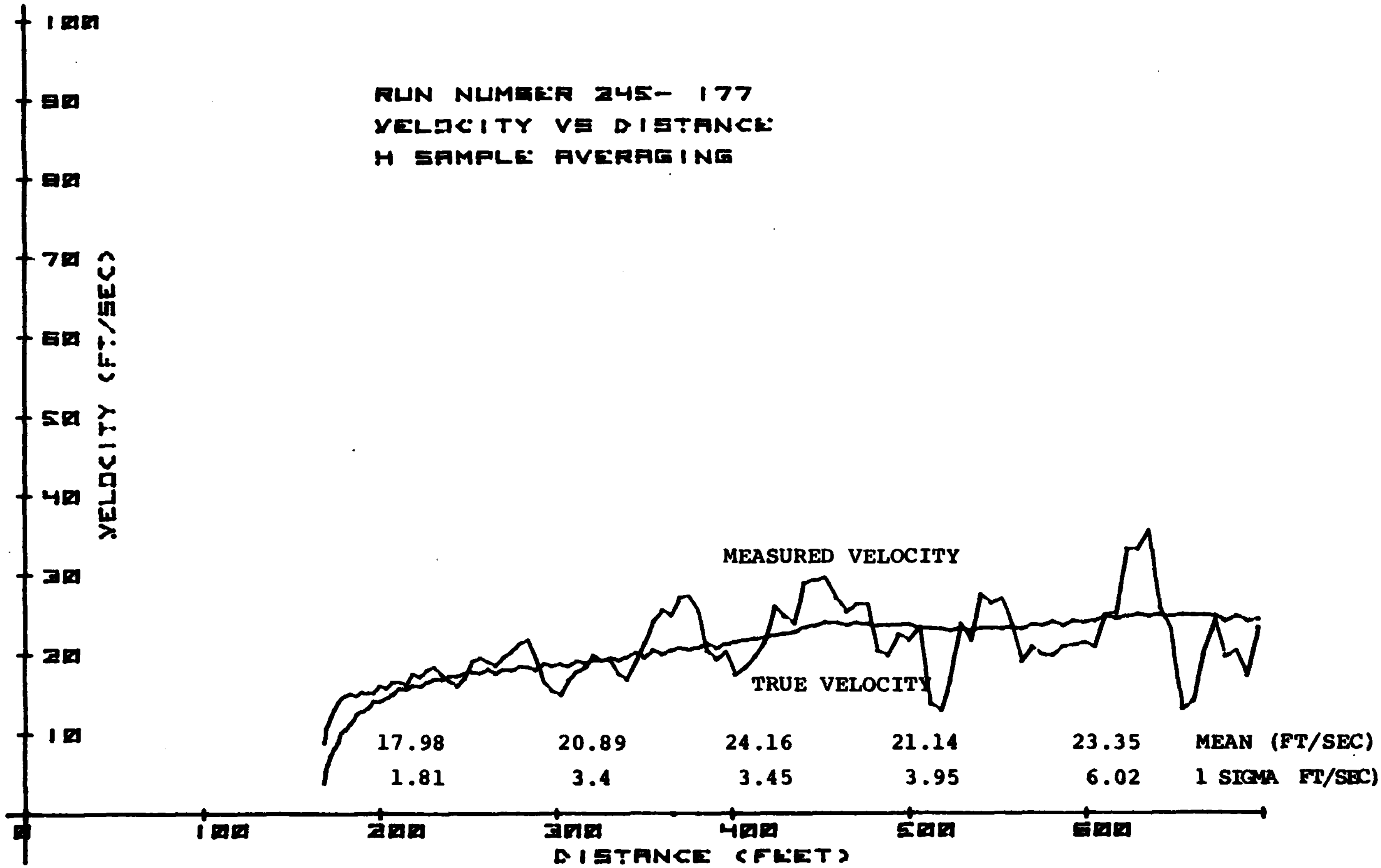

FIGURE 4-16C. 15 MPH TRUCK TEST - 15' HEIGHT

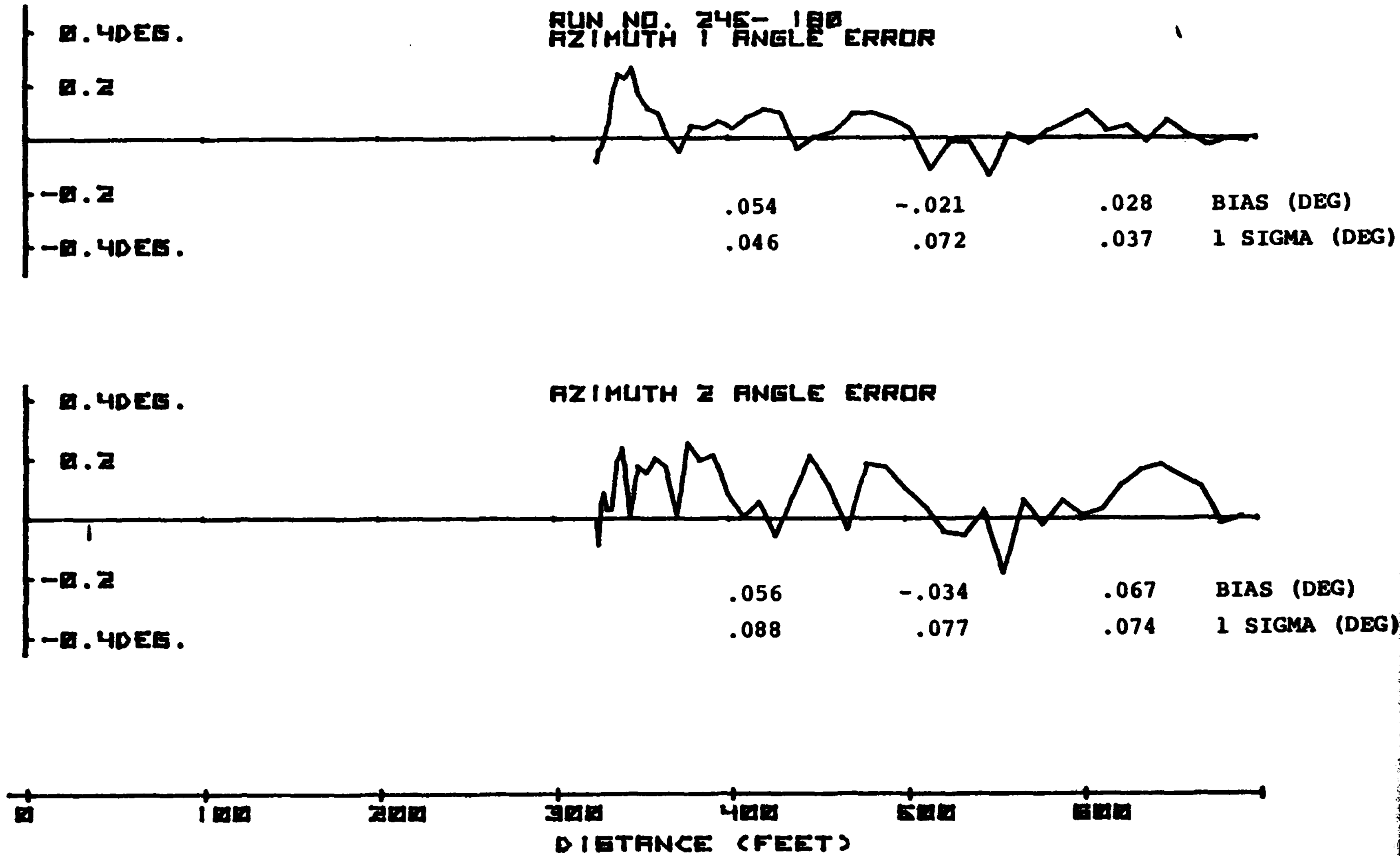

FIGURE 4-17A. FAST STOP 30 MPH TRUCK TEST - 15' HEIGHT

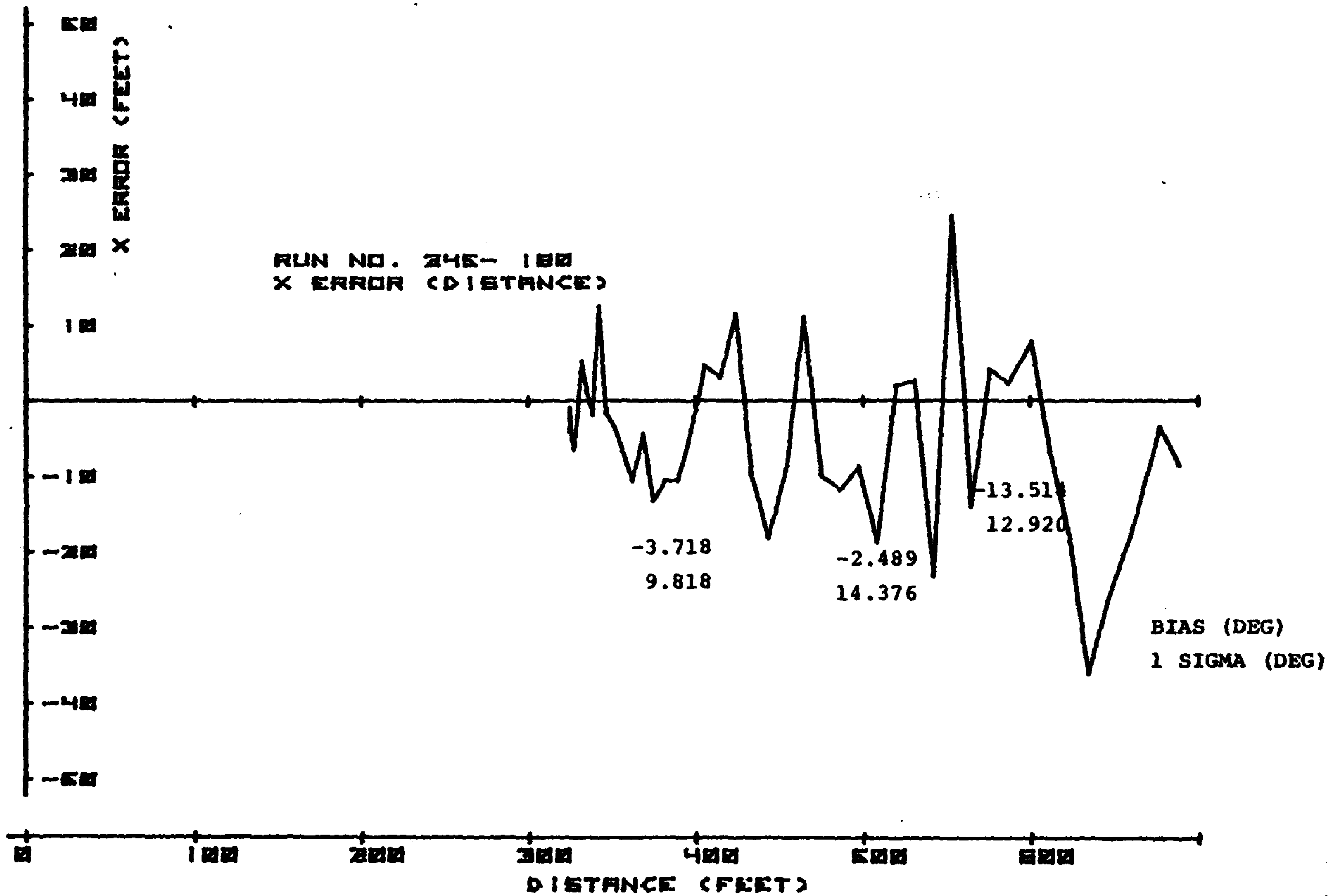

FIGURE 4-17B. FAST STOP 30 MPH TRUCK TEST - 15' HEIGHT

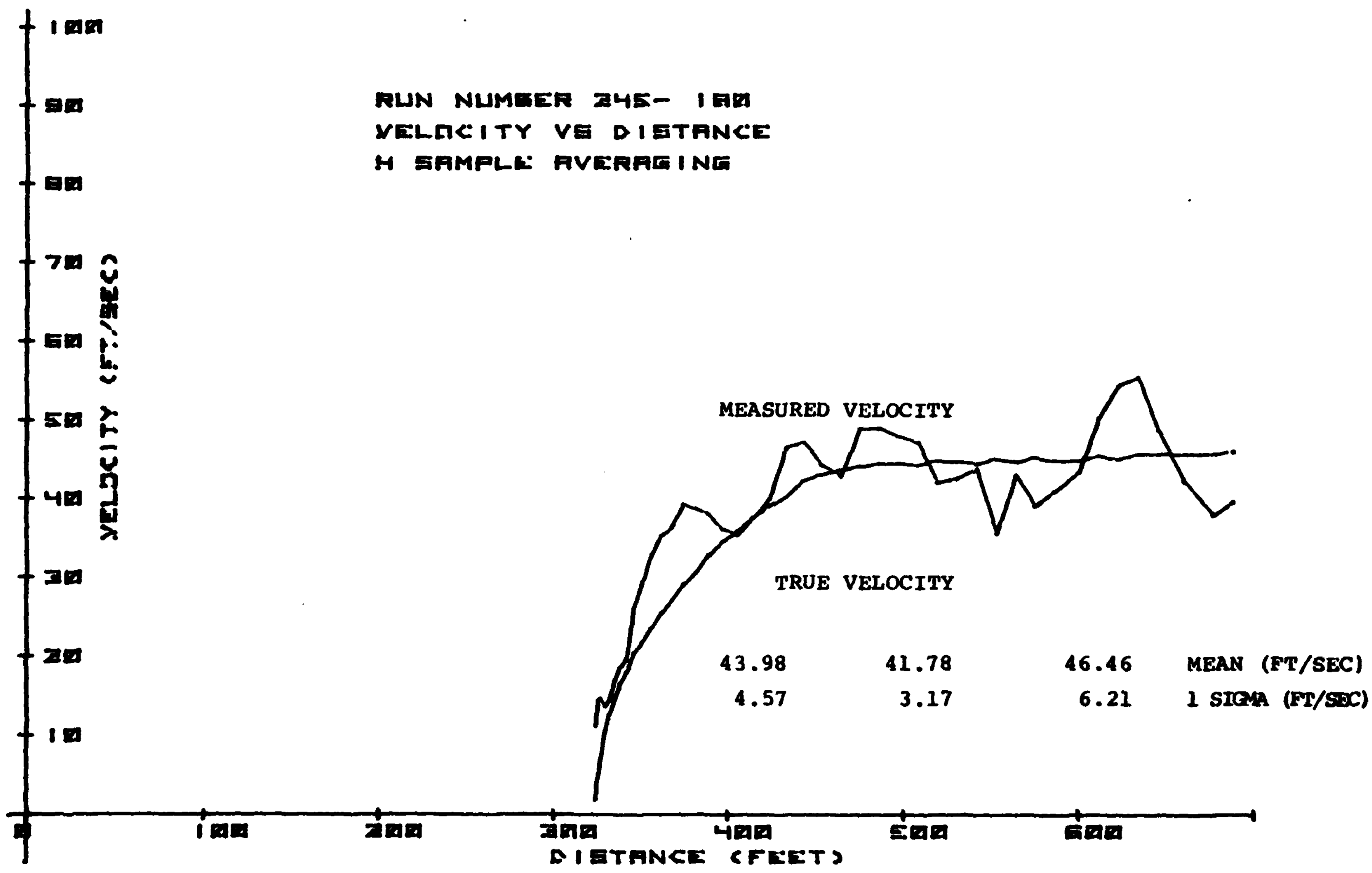

FIGURE 4-17C. FAST STOP 30 MPH TRUCK TEST - 15' HEIGHT

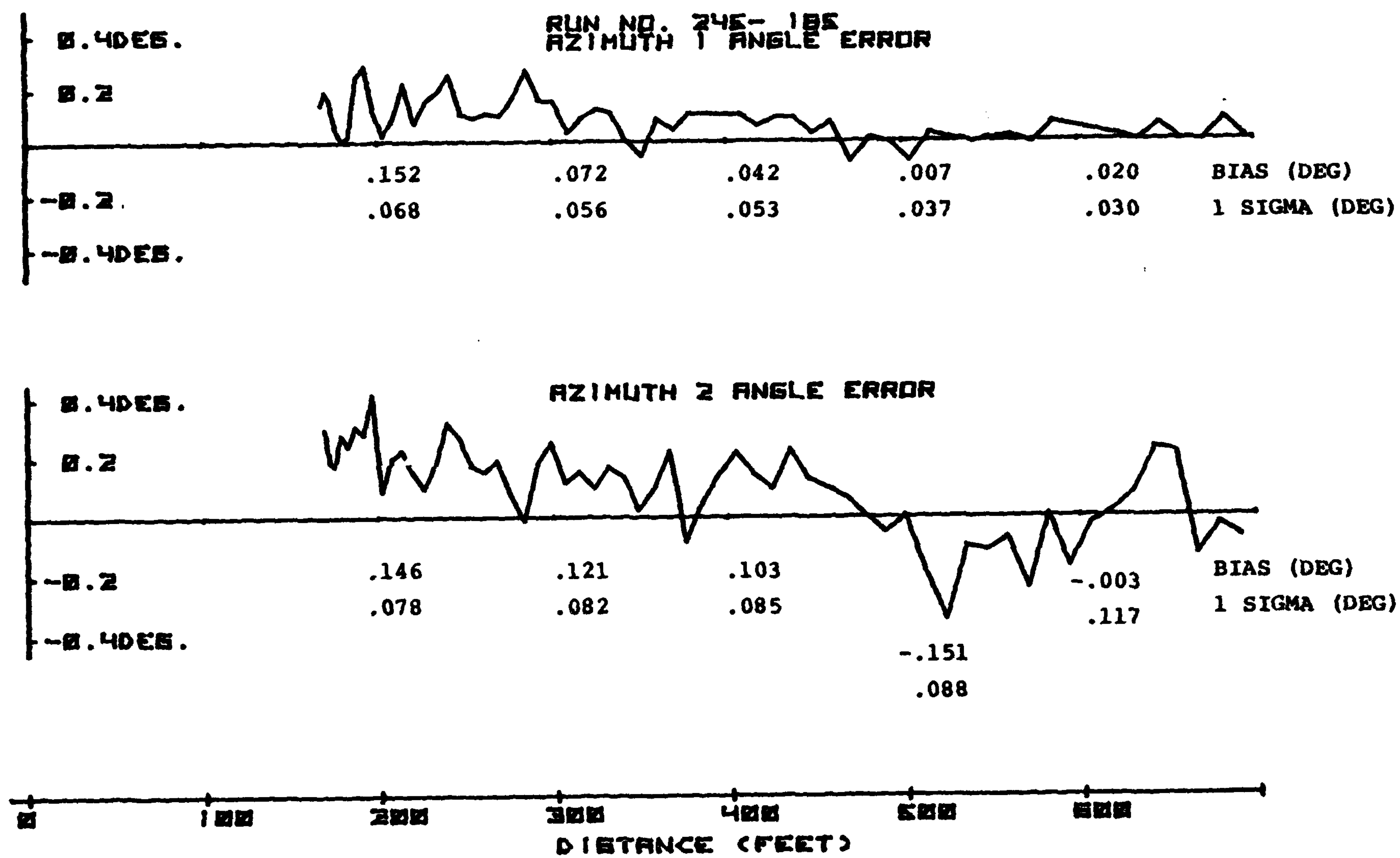

FIGURE 4-18A. 30 MPH TRUCK TEST - 10' HEIGHT

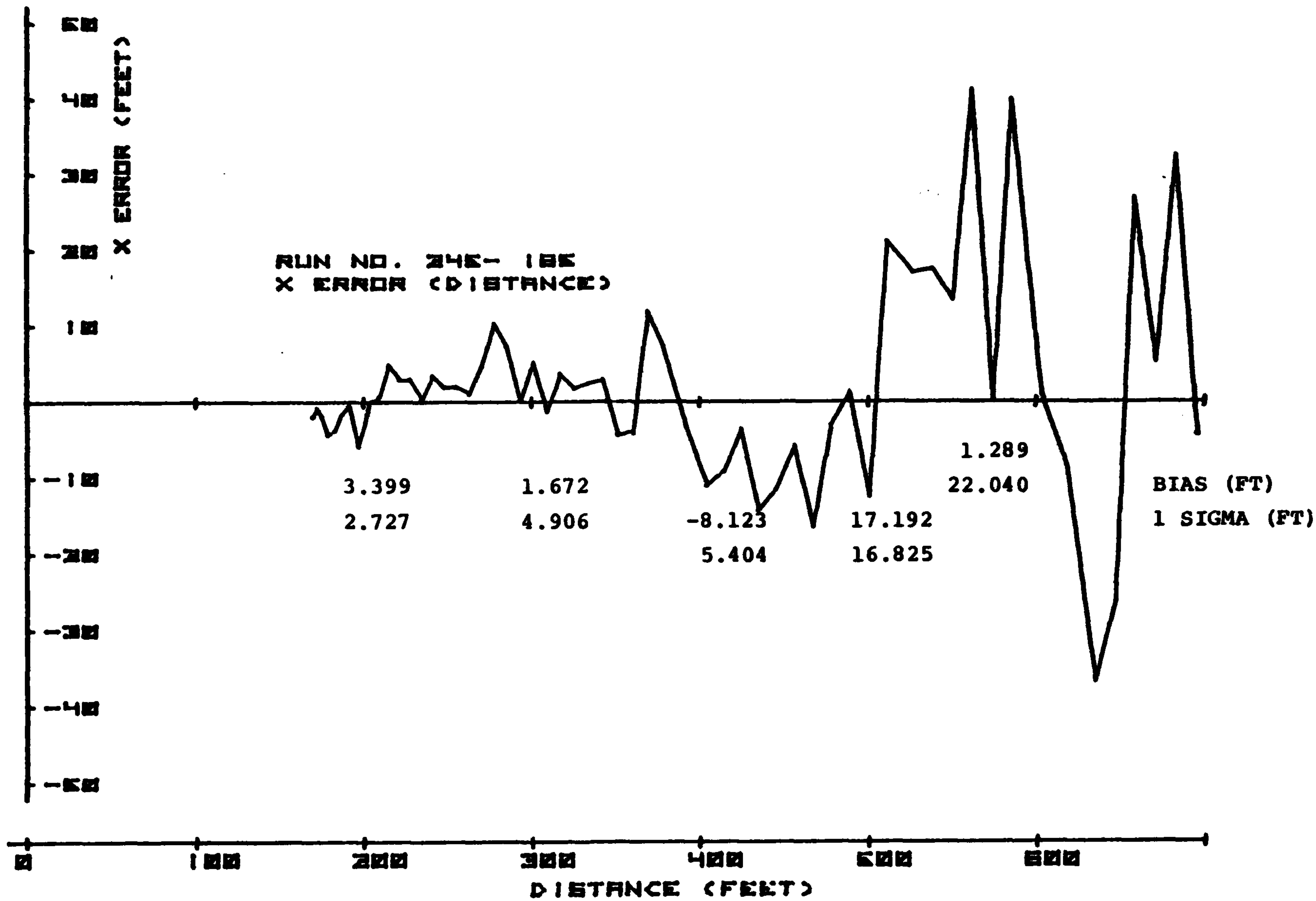

FIGURE 4-18B. 30 MPH TRUCK TEST - 10' HEIGHT

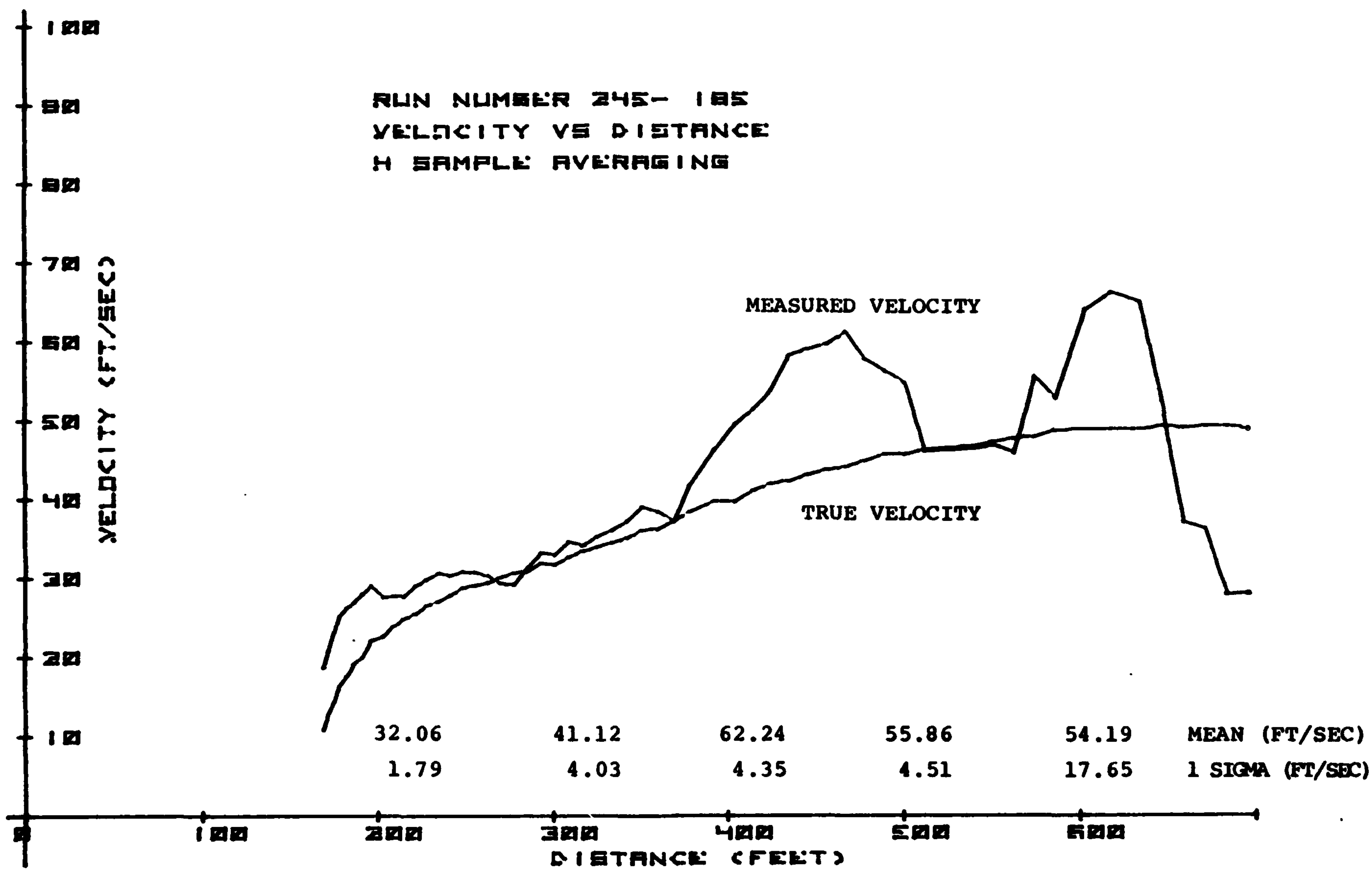

FIGURE 4-18C. 30 MPH TRUCK TEST - 10' HEIGHT

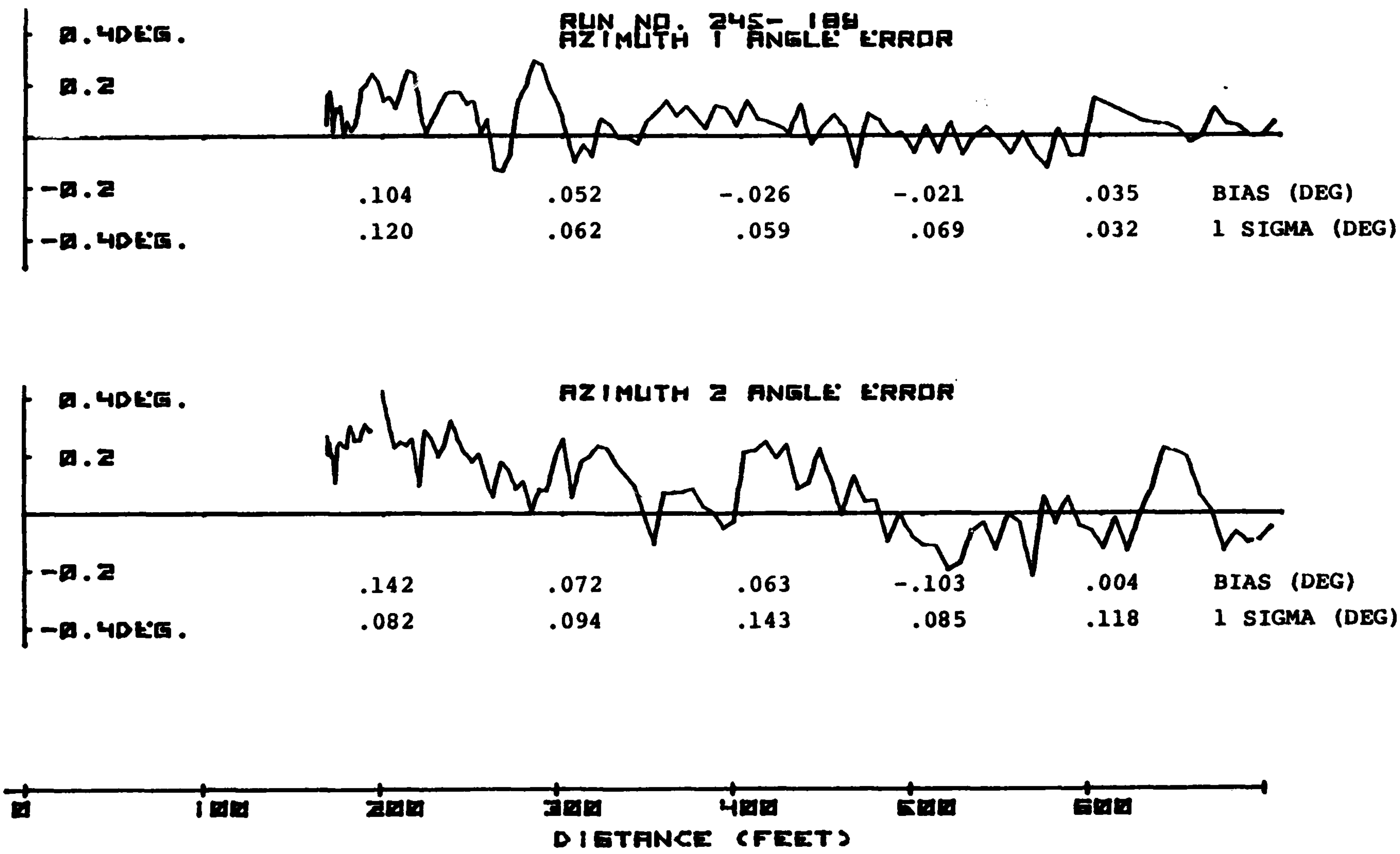

FIGURE 4-19A. 15 MPH TRUCK TEST

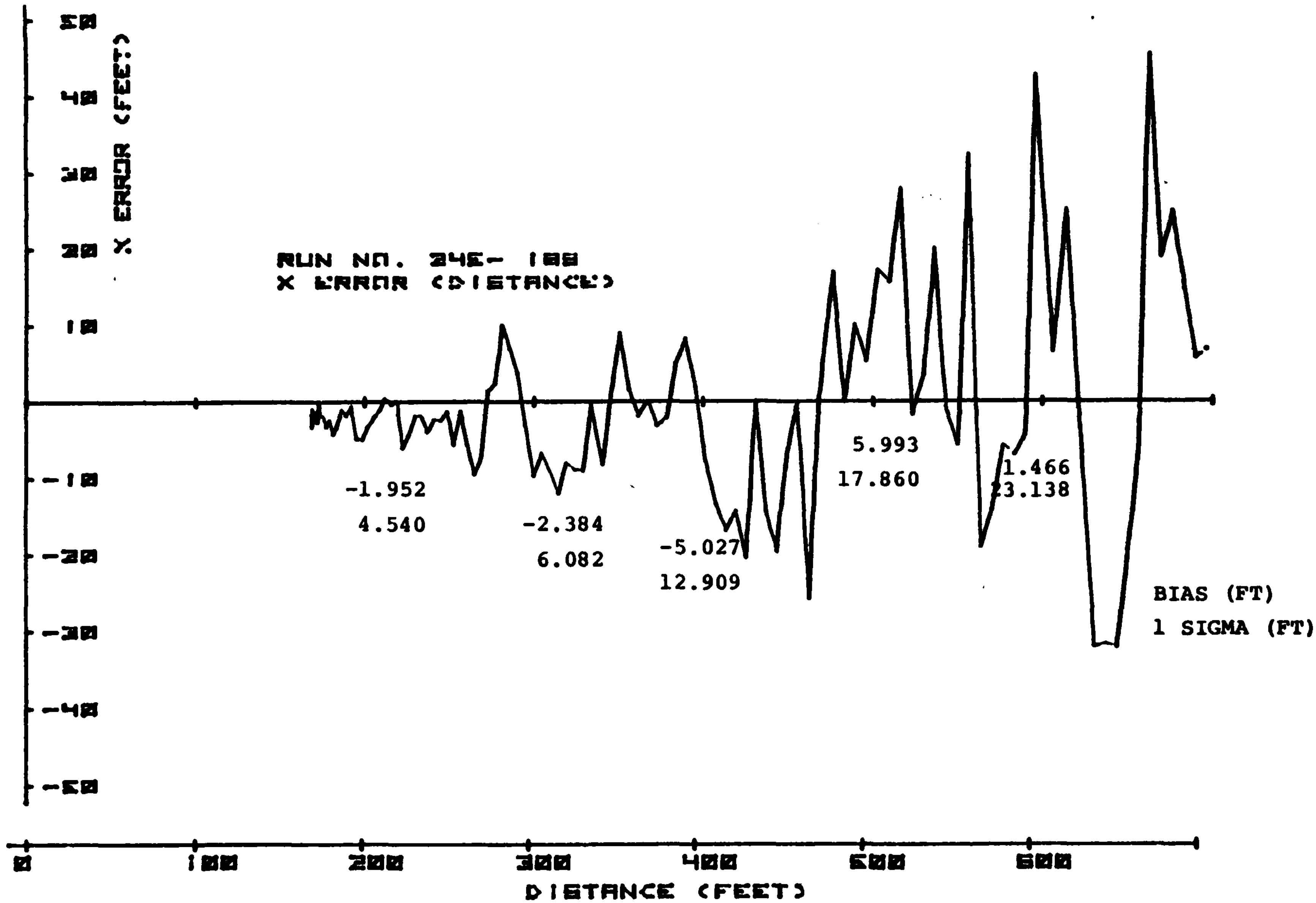

FIGURE 4-19B. 15 MPH TRUCK TEST

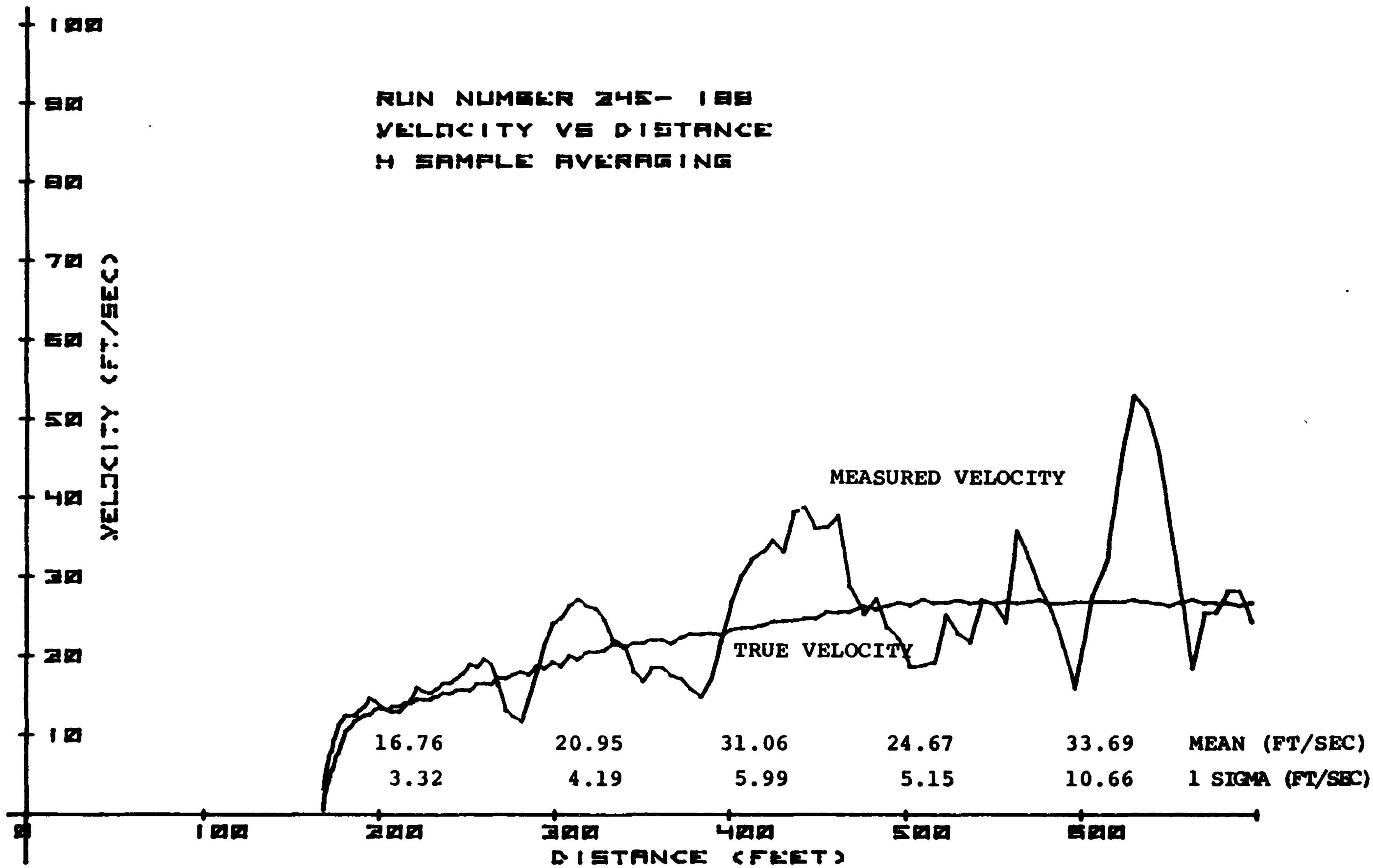

FIGURE 4-19C. 15 MPH TRUCK TEST

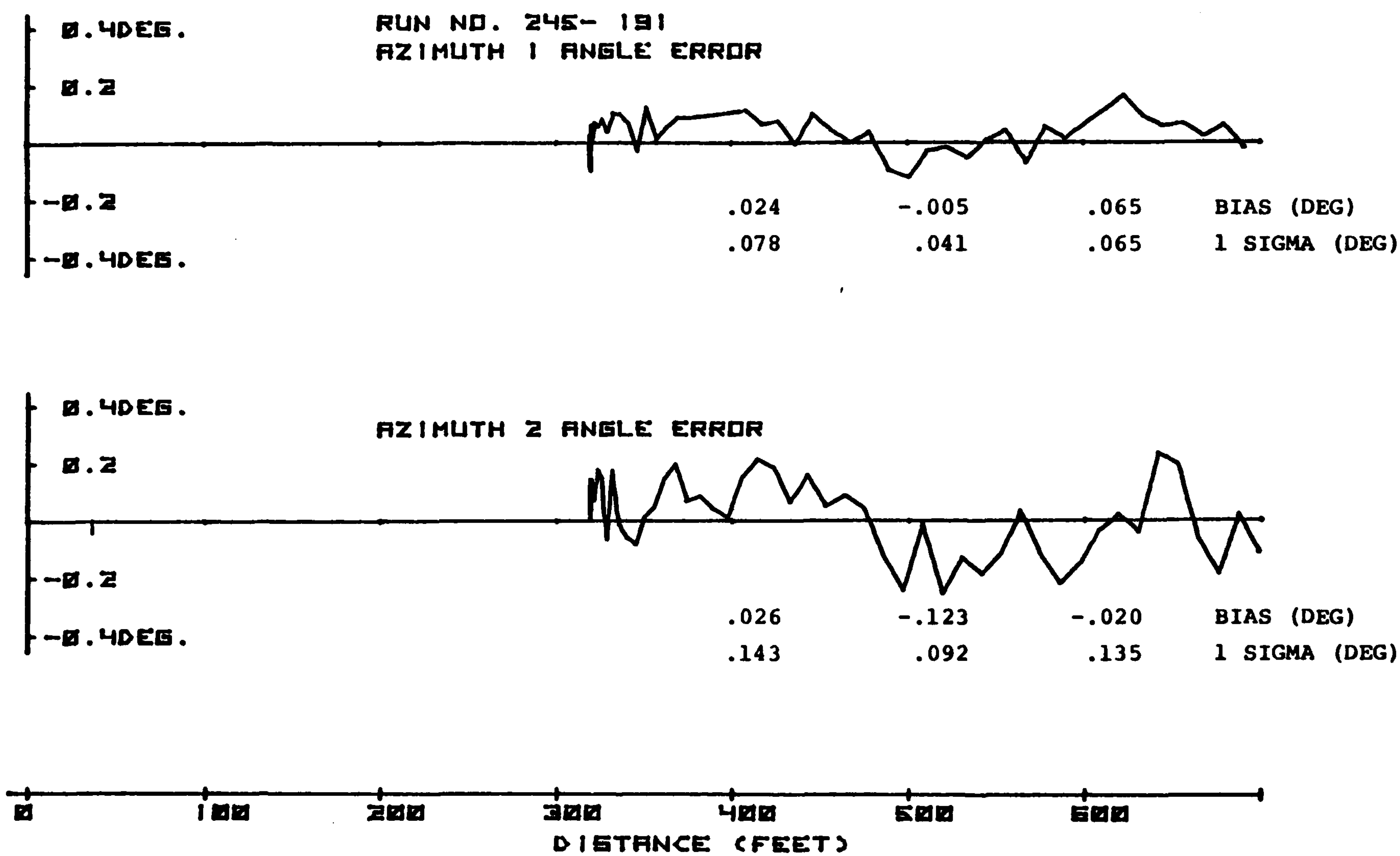

FIGURE 4-20A. FAST STOP 30 MPH TRUCK TEST - 10' HEIGHT

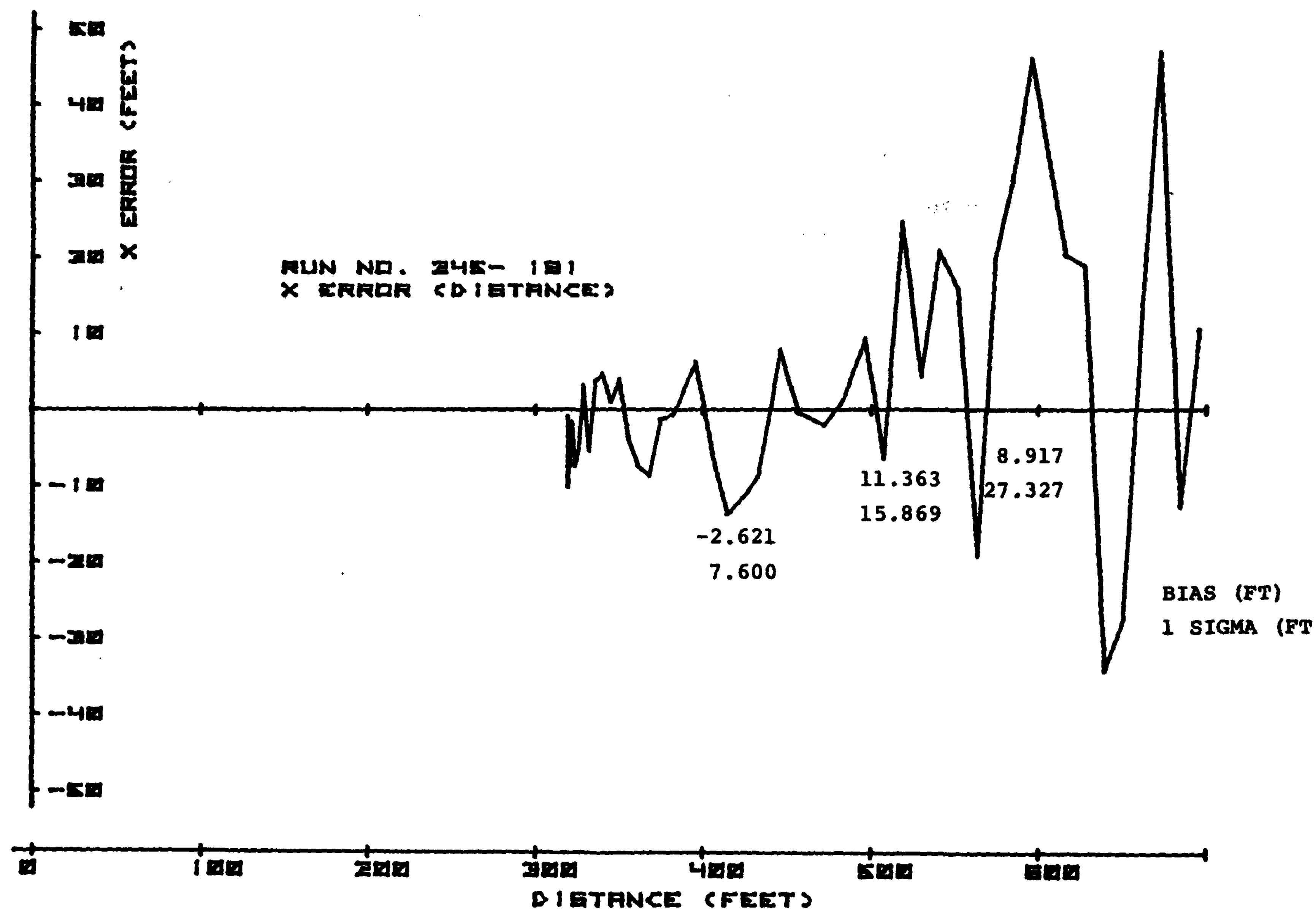

FIGURE 4-20B. FAST STOP 30 MPH TRUCK TEST - 10' HEIGHT

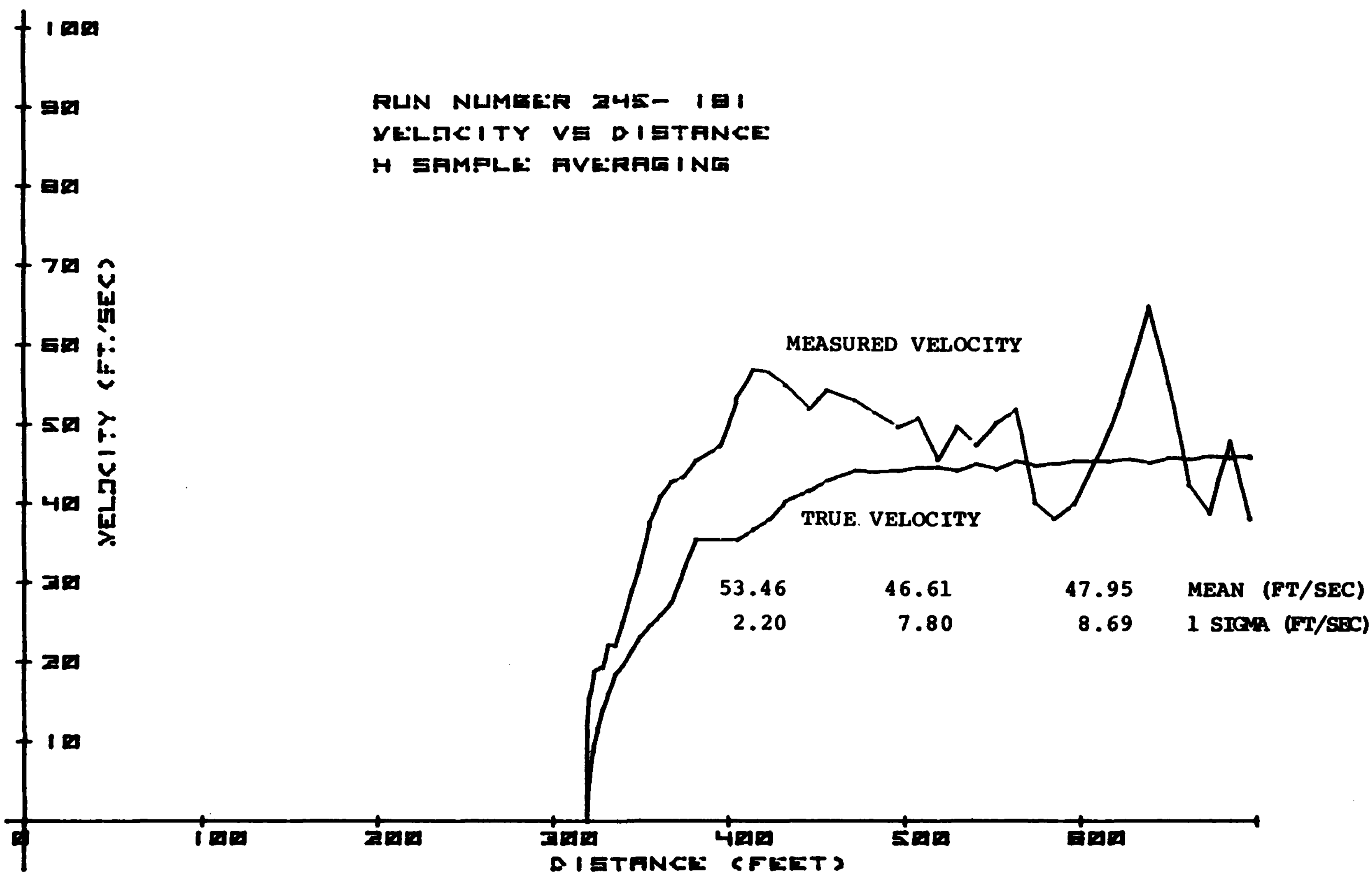

FIGURE 4-20C. FAST STOP 30 MPH TRUCK TEST - 10' HEIGHT

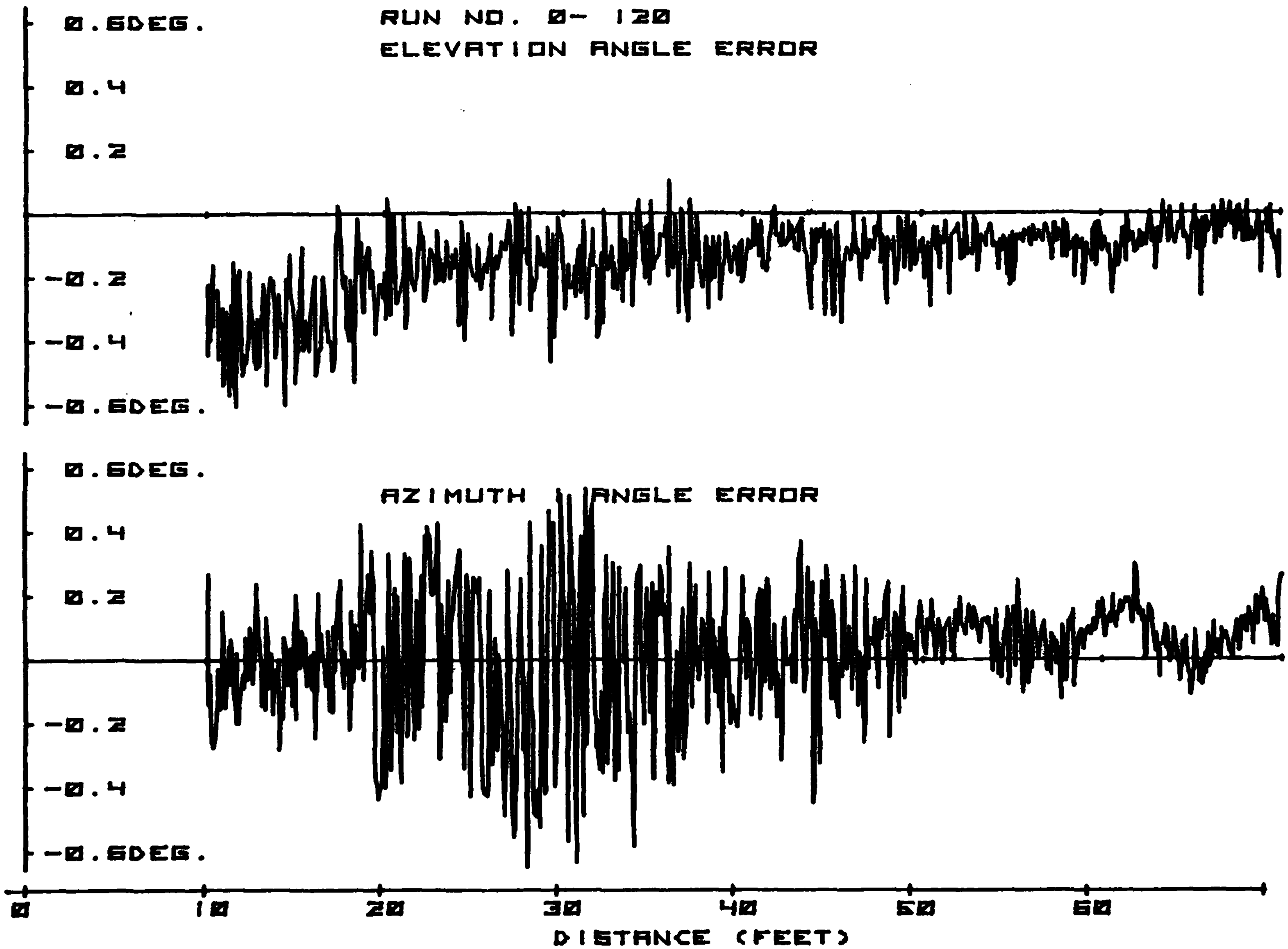

FIGURE 4-21. DOUBLE BOUNCE TEST

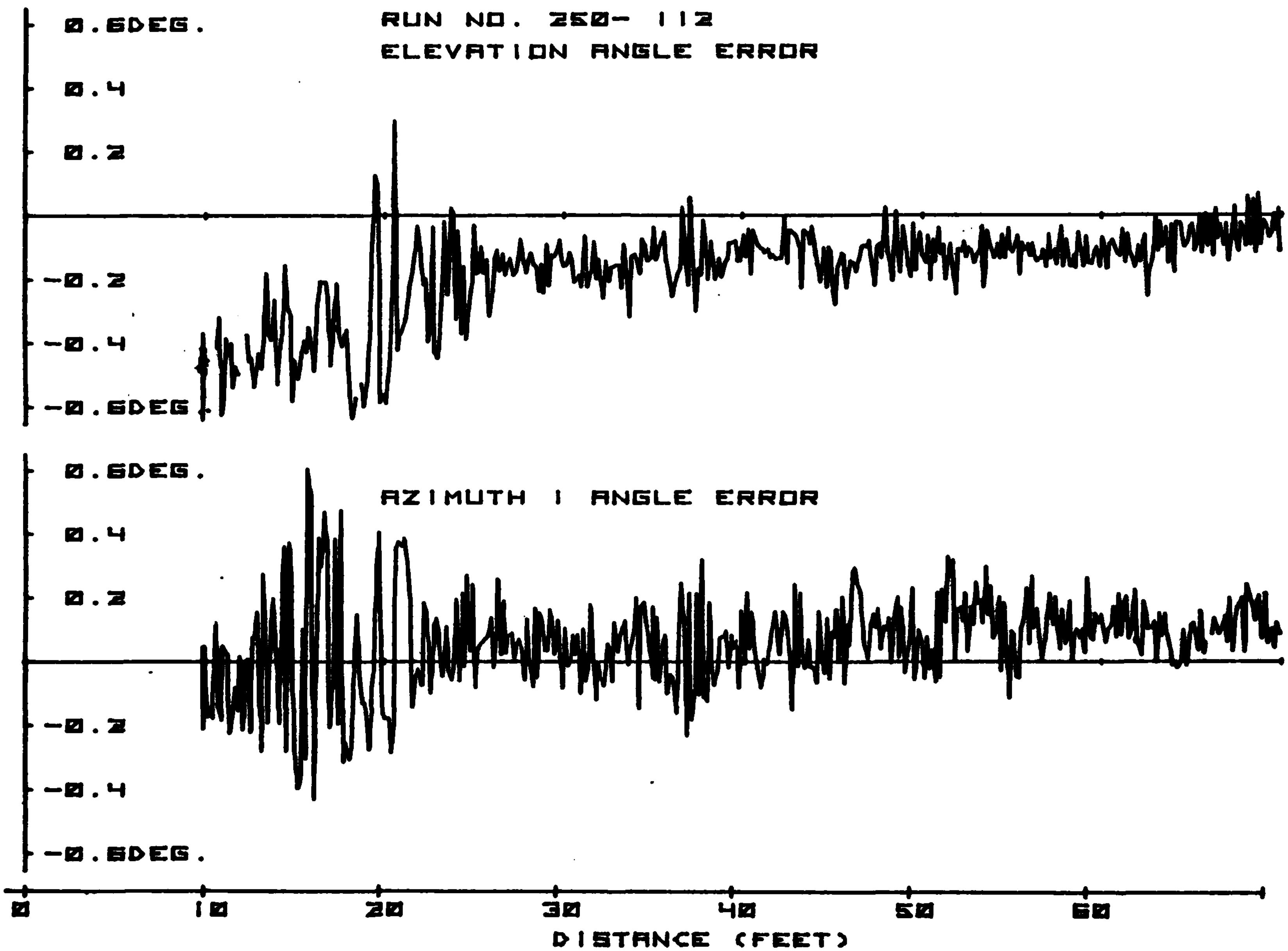

FIGURE 4-22. DOUBLE BOUNCE TEST REPEAT

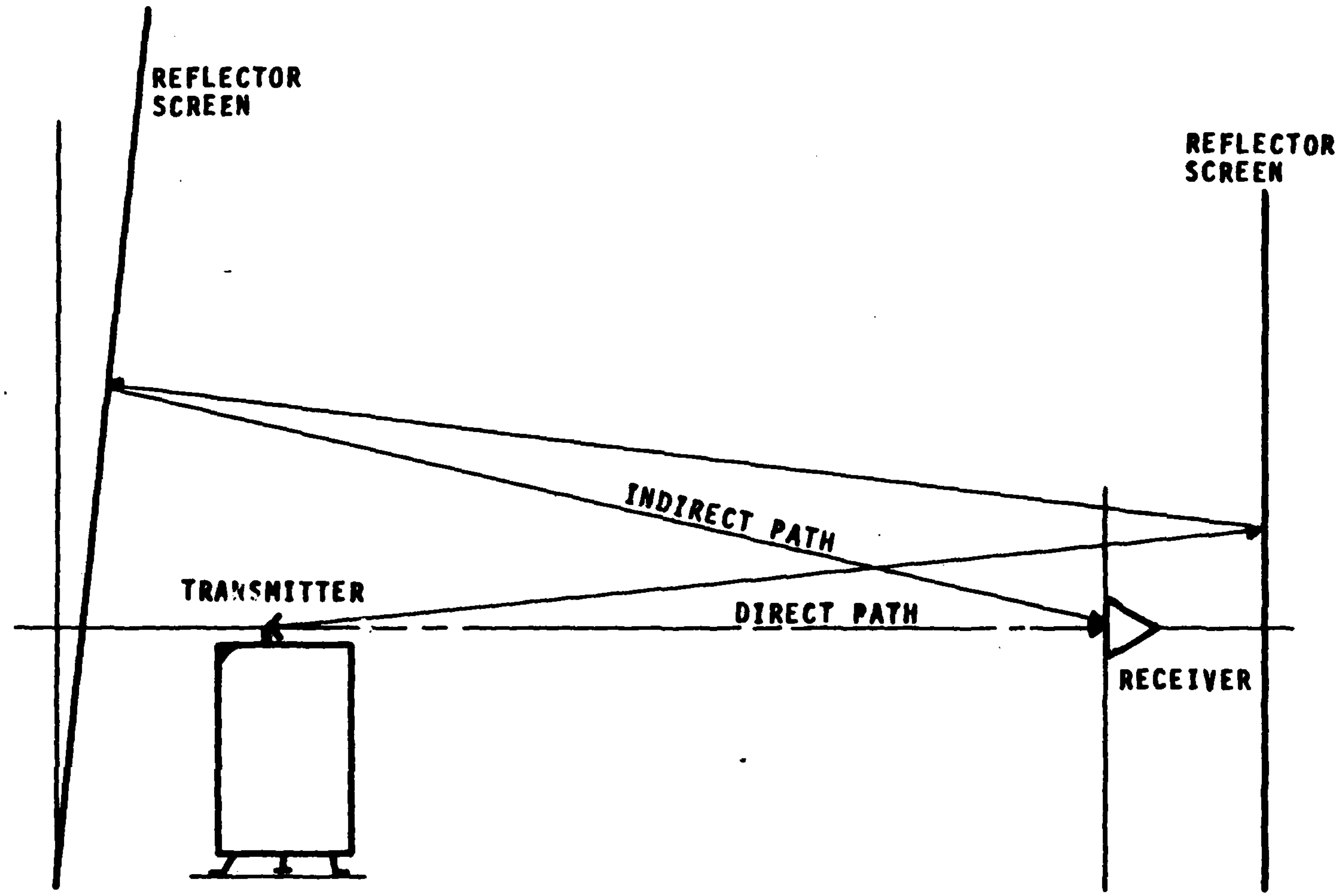

FIGURE 4-23. DOUBLE BOUNCE GEOMETRY

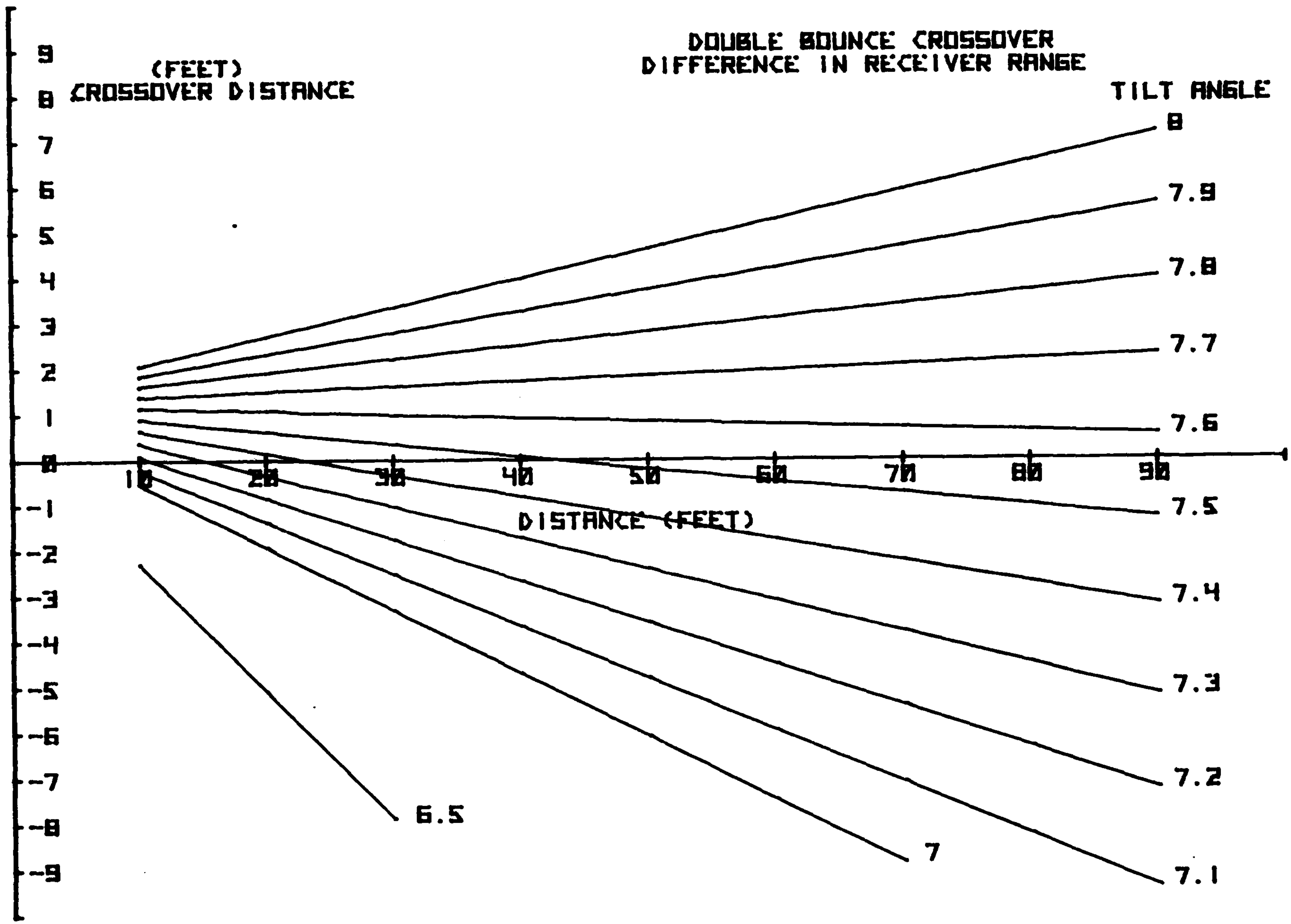

FIGURE 4-24. DOUBLE BOUNCE CROSSOVER

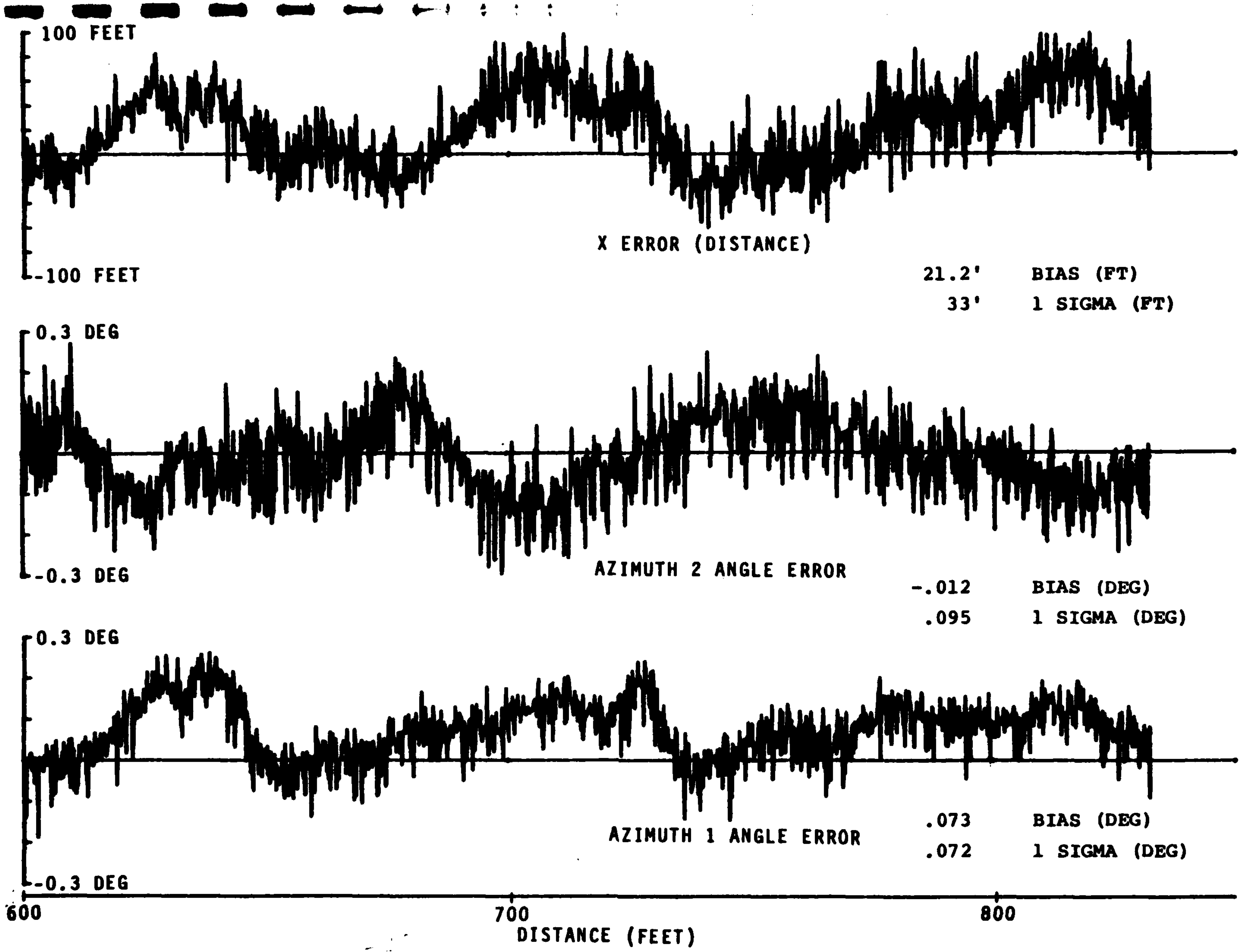

FIGURE 4-25. MULTIPATH AZIMUTH ANGLE AND DISTANCE ERRORS

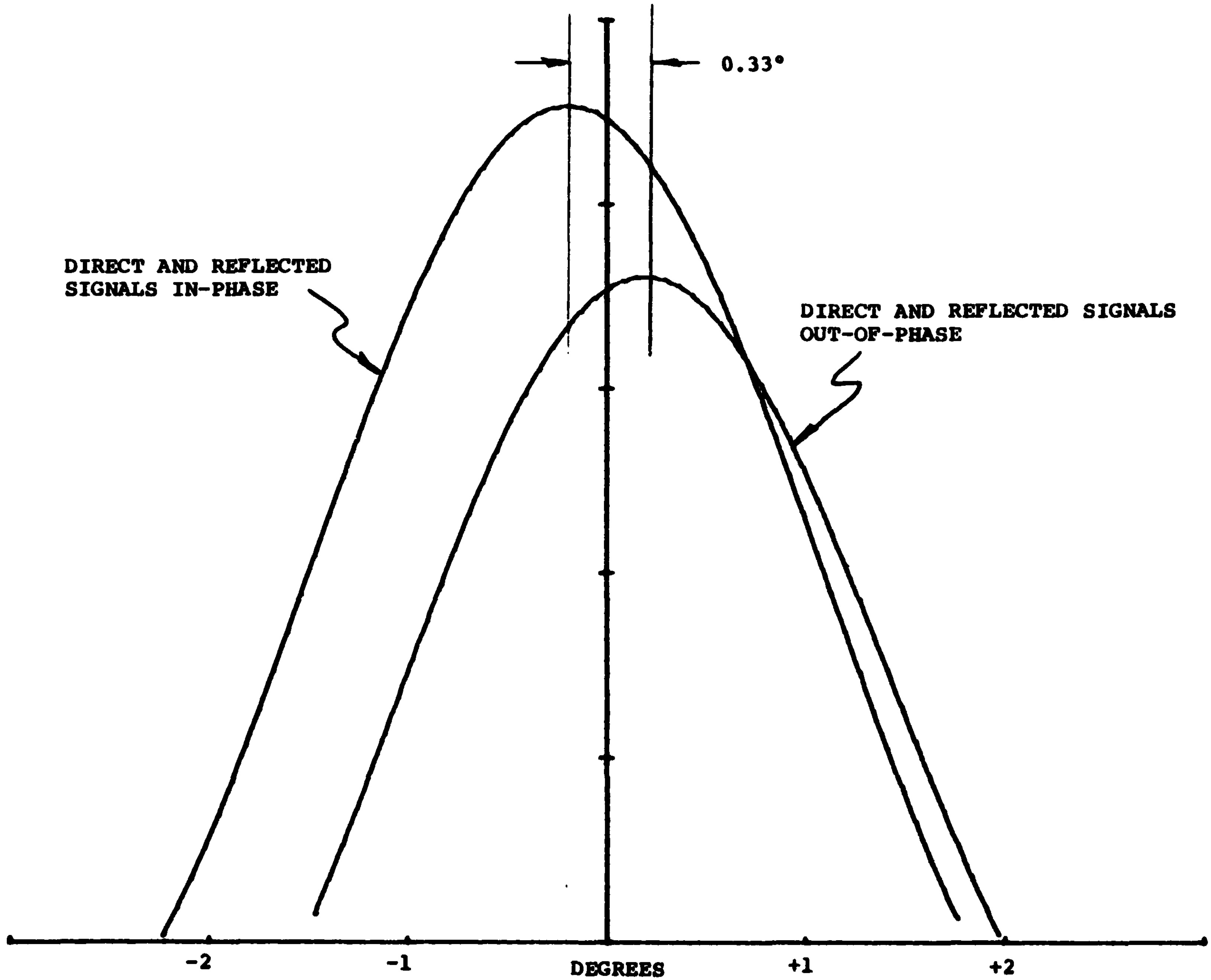

FIGURE 4-26. DIRECT PLUS REFLECTED COMPOSITE BEAM PATTERNS

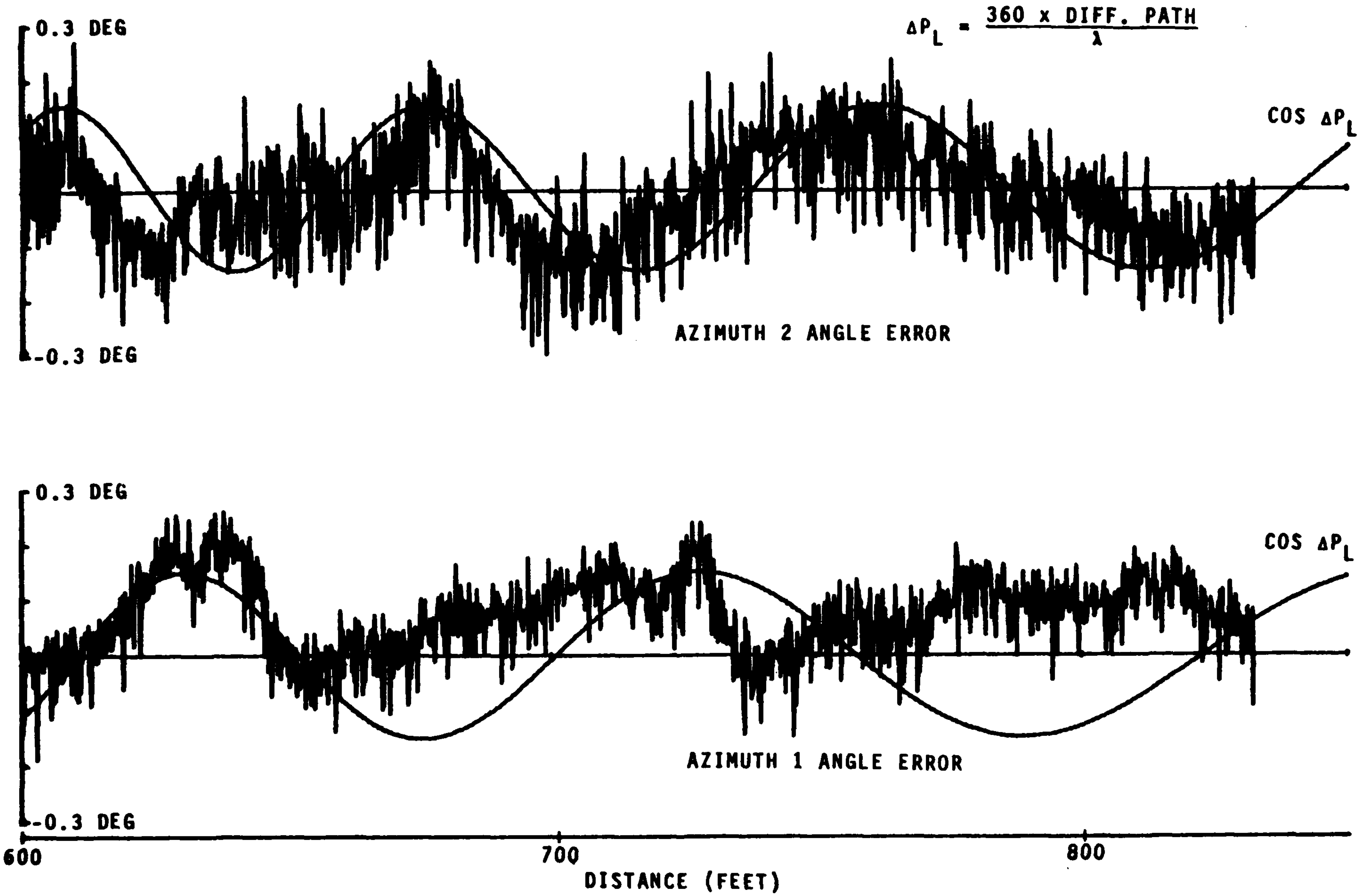

FIGURE 4-27. COSINE OF PATH LENGTH DIFFERENCE BETWEEN DIRECT AND GROUND REFLECTED SIGNALS AND AZIMUTH ANGLE ERRORS

5.0 NAVTOLAND SENSOR REQUIREMENTS

Terminal guidance for aircraft returning to ships with small landing zones is currently limited to pilot visual techniques. Limitations on the pilot's visibility and on his visual sensing in obscured conditions and/or during conditions of extensive deck motion become increasingly intolerable as the dependence upon air operations increases. The modern Navy, depending upon helicopters, and new types of V/STOL aircraft, cannot afford to limit its operations as a result of darkness, fog, cloud cover, or high seas, if it is to carry out its mission. A system of guidance that directs the approach maneuver, the deck alignment and the actual touchdown on the pad is an important next step in the development of the air capable ships.

The landing pad, on the typical small ship can be as small as 40' by 40'. The restraining gear that grabs and holds the aircraft once deck contact is made, has an acceptance diameter in the order of six feet. The most critical parameter that must be met by the NAVTOLAND sensor is absolute accuracy on the pad. The goal of ± 1 foot has thus been set at the touchdown point. Absolute accuracy requirements, as a function of distance from touchdown do relax from this severe requirement. However, within 300 feet of the ship it is well to point out that required positional accuracies approach values are seldom achieved by conventional systems in conventional flight.

As the aircraft considered for NAVTOLAND application will be flying curved profiles, particularly in the elevation plane, the NAVTOLAND sensor is also expected to provide rates. The required accuracy for rate increases as the approach proceeds and reaches its most demanding level of ±1 fps within 300 feet of touchdown.

A factor contributing to the guidance sensor performance is the ship's motion which produces both lateral and vertical translation of the landing zone. To maintain basic guidance sensor accuracies, the ship motions must be precisely measured in real time to provide stabilized

(or compensated) guidance data transmitted up to the approaching aircraft. Ships motion data is necessary independent of the guidance sensor technique. The requirements and techniques for determining ships motion are discussed in Section 5.2. Conversely, regardless of ships motion, the basic guidance sensor inherently must provide the basic accuracies delineated previously.

Another critical factor in NAVTOLAND sensor considerations is the transitioning of navigation commands from the enroute or far out approach guidance sensor (TACAN) to the landing guidance sensor. This change over of guidance information must be accomplished, accurately and smoothly without creating any stress situation, either on the aircraft or their operators.

Finally, although not a specified NAVTOLAND requirement, it is extremely desirable to be able to utilize equipment already in the Navy's inventory. It is self evident, that the use of compatible hardware will take advantage of developed expertise, reducing the auxiliary needs for taining, spare parts, etc., when the system becomes operational.

5.1 TRISCAN PERFORMANCE

The basic premise behind the application of the TRISCAN triangulation technique is that with the present angular measurement accuracy capabilities, the resultant X, Y, Z coordinate computation of aircraft position would be adequate. As demonstrated by the test results, except for double bounce runs inside of 40 feet, actual system performance was well within the target limits. Accordingly, the position error at touchdown was seen to be significantly better than ±1 foot, reaching the limits of ±1 foot about 100 feet from the transmitting stations. Therefore, assuming a 40 foot baseline, TRISCAN will provide aircraft position to an accuracy of ±1 foot anywhere over the landing area with range rate accuracies better than 1 fps.

Even under simulated worse case multipath conditions, vertical and parallel reflecting surfaces behind transmitters and with the receiver at the transmitter

antenna height, system position performance was not affected to any significant degree beyond 40 feet from the station. Closer in, the maximum position errors were found to be comparable to the target accuracy requirements. At further ranges, where the position accuracy requirements are somewhat relaxed, the data verifies that TRISCAN can provide aircraft position to within ±10 feet at 300 feet and within ±100 feet at 1,000'.

Recognizing the need for accurate and timely range rate information, TRISCAN will provide a dual mode range rate computation facility. In the close-in critical portion of the sector (300 feet to touchdown), the basic triangulation derived X, Y, Z coordinates of the aircraft position will be used directly to compute range rate from the individual $\dot{X}$, $\dot{Y}$, and $\dot{Z}$ velocity vectors with accuracies better than 1 fps.

Analysis of the data revealed that range rate can be calculated to accuracies better than ±1 fps within 300 feet range directly from the position coordinate information. Beyond this range, the range rate noise was such that large integration times were required to minimize noise errors. Because this produced an unacceptable lag in the range rate answer, a one way doppler range technique is now included in TRISCAN; and computer simulation has verified its applicability.

As mentioned earlier, TRISCAN is a modification of the existing U.S. Navy/AIL C-SCAN (AN/SPN-41, AN/ARA-63) system and has demonstrated an operational range of 10 miles. Therefore, the guidance transitioning from TACAN to TRISCAN can be accomplished while the aircraft is still far removed from the final landing approach phase. Thus, required aircraft maneuvers, during the transition, can be performed over a relatively long time period, so that these maneuvers can be accomplished smoothly without imposing any unreasonable requirements on either aircraft or crew.

5.2 SHIPS MOTION SENSING

Precise and timely measurement of ships motion is mandatory to enable the guidance system to provide the accurate navigation information required during the approach and landing phases. Since, worst case, there can be direct one-to-one relation between ships angular motions (roll, pitch and yaw) and the angle guidance data, these motions must be accurately determined to avoid degradation of the basic guidance information itself. Additionally, linear ships displacement (heave, surge and sway) information may be needed, albeit to a lesser accuracy, to minimize "deck chasing" type maneuvers by the approaching aircraft.

Another factor is the information required by the pilot during the final maneuvers just prior and at touchdown. This would be a "deck level signal" indicating it is (or will be) safe to touchdown. The signal would be some function of the instantaneous angular and linear ships motion parameters and/or derived from a ships motion predictor. While the investigation and evaluation of real time techniques of measuring ships motion is reported herein, the related studies of ships motion forecasting methods are outside the scope of this specific project and are not discussed any further.

Independent sensors, one for angle rotational measurement and one for linear motions, are required; and they are individually discussed later. From several reports[1,2,3], the following model set of ship motion has been established as the maximum linear range of the parameters to be measured by the linear motion transducers to provide heave, surge, and sway stabilization data. The selection criteria were values that would represent the absolute limits of allowable ships motion during the approach and

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[1] NSRDC Report 3868, July 1973, Response Predictions of Helicopter Landing Platforms for USS Belknap (DLG-26) and USS Garcia (DE-1040) Class Destroyers.

[2] David Taylor Model Basin Report SPD-525-01, Trial Results of Ship Motions and Their Influence on Aircraft Operations for ISCS Guam.

[3] SPD 556-01, NSRDC, Influence of Ship Motions on Operations of SH-2F Helicopters.

landing phase; and that if these limits were exceeded, no approach and/or landing maneuvers would be attempted. Also, these values are a composite representing the maximum reported for each parameter.

Heave	18'	Double Amplitude
Surge	5'	Single Amplitude
Sway	6'	Single Amplitude
Roll	19°	Single Amplitude
Pitch	7°	Single Amplitude
Yaw	1.5°	Single Amplitude

5.2.1 ANGLE SENSORS

As shown earlier, the TRISCAN tests in conjunction with a modified AN/ARA-63 decoder have demonstrated angular accuracies better than 0.2°, even when the receiver is within 20 feet from the ground station. To maintain this level of guidance performance on board ships, the requisite measurements accuracies of ships angular motion should be better by an order of magnitude or about 0.02°. This includes all errors associated with such devices, not only static errors but also velocity lag, acceleration effects and followup errors from the sensor to the guidance system itself.

Obviously, a prime candidate sensor for ships motion is the Gyrocompass system carried aboard all Navy ships. The Mark 19 Gyrocompass system, installed on larger ships such as the LHA, LPH and DE-1052 class ships provides roll and pitch in addition to heading data. Smaller ships, however, carry either Mark 11, the Mark 23 or Mark 27 Gyrocompass systems that provide heading only. There are no known standard Navy equipments that measure ships linear motion.

The NAVTOLAND program objective is to provide the capability for aircraft operation from the above class ships as well as from "aviation facilities ships" (non-aviation ships); and at this time there is some uncertainty

as to whether all the aviation facilities ships will have (or do have) Mark 19 Gyrocompass or equivalent systems. Nevertheless, because the Mark 19 Gyrocompass system does provide the required data, it was evaluated to determine its applicability to the problem of providing accurate ship motion data.

The governing Gyrocompass specification[1] MIL-G-17012F (Ships) 24 August 1967, enumerates roll and pitch accuracies of $\pm$ 0.03° (small angle Scorsby)[2] and $\pm$ 0.05° (large angle Scorsby). The small angle Scorsby test more closely duplicates conditions that would be encountered during VSTOL approach and landing operations. Comparable heading errors are 0.15° and 0.2° for small and large angle Scorsby tests.

Presumably, based on the equipment specification defining factory tests, the MK 19 might be a satisfactory source of ships motion data. There are, however, questions whether these accuracies are maintained after shipboard installation and use. Although the manufacturer and several Navy groups assert operational performance is held to the factory tolerances, other groups question whether actual performance stays within 0.1° accuracy under day-in and day-out at sea operation.

Even assuming that the MK 19 is suitable, the data must be transmitted to the guidance system via a repeater. Again, it cannot be assumed that on every ship the Gyro system has excess repeater capacity that can accommodate the guidance system. Additionally, to maintain accuracy, a two speed repeater is required and the net costs of this repeater plus the added ships cabling between the Gyro station and guidance system would be considerable.

[1] Although the MK 19 is now superseded by the more advanced and accurate WSM-12, the Navy does not intend to replace existing Gyrocompass installations with improved types.

[2] "Scorsby" describes a Test Stand Evaluation procedure.

Considering these factors, marginal accuracy as far as TRISCAN requirements are concerned, uncertainty of Gyrocompass data availability and finally the costs to data link the Gyrocompass to the TRISCAN, suggest very strongly that a separate dedicated sensor system be made integral and part of a "stand alone" TRISCAN guidance system.

Several types of transducers that measure the angle of tilt off vertical are available commercially. They are all gravity reference sensors and are known by a variety of names such as inclinometers, tiltmeters, vertical sensors, level sensors, pendulums, and gravity sensing electrolytic transducers. Of course, the common vertical Gyro is also a popular device that provides "off-vertical" angle information. Additionally, several manufacturers have proposed designing and building specials using micro-accelerometers to obtain the required performance characteristics.

These various transducers were examined and after considerations of life (MTBF), environmental and temperature ranges, construction, and size, acceleration effects, cost, present and projected performance accuracies, and availability, a recently announced (October 1976) inclinometer manufactured by Schaevitz Engineering was selected as the most suitable device for further evaluation.

The other devices surveyed had either known sensor deficiencies and/or significant data was not readily available. Vertical gyros, for example, have limited life--about 1000 to 2000 hours MTBF--and are relatively expensive. Precision pendulums had a best specified accuracy of $\pm$ 0.1° with limited range of $\pm$ 12°, inadequate for roll and somewhat restricted temperature range. Electrolytic type transducers, although relatively inexpensive, generally have a limited life specified (2000 hours) and do not have extended angular range capabilities with high precison. Also, at this time, because "off-the-shelf" devices are available that appear capable of meeting the needs for the ship's angle motion sensor, we did not feel it was appropriate to solicit special developments with their attendant costs and uncertainties.

The Schaevitz inclinometer is self-contained and uses a closed loop, gravity-referenced sensor in a

flexure-supported torque balance system. Its pertinent catalog specifications are (for a ± 30° range):

		RELATED ANGLE SPECIFICATION
Output Voltage	± 5 V Full Scale	(± 30°)
Linearity	± 0.02% FS*	(± 0.012°)
Hysteresis and Resolution	± 0.0001% FS*	(± 0.00006°)
Noise Output	2 mv rms	(0.012° rms)
Zero Offset	0.1% FS	(0.06°)
Sensitive Axis Alignment	5 mv	(0.03°)
Frequency Response	3 db @ 30 Hz	
Operating Temperature	0°F to 160°F	(-18°C to +71°C)
Temperature Coefficient		
Null	0.003% FS/°F	(0.0009/°F)
Scale Factor	0.003% of reading/°F	(or 0.144° over temp range at 30°)
Cross Axis Sensitivity	50 mv/g	0.3°/g
Shock	1000 g, 11 ms	
Vibration, sinusoidal	0.2 inch double amplitude from 0 to 20 Hz 10 g peak, 20 Hz to 50 Hz. 50 g peak, 50 Hz to 2000 Hz.	
Humidity, salt spray, fungus, sand	O-ring sealed to MIL-STD-202 method 112, condition B.	

* Full range defined as "from negative full range to positive full range."

The ideal transducer location, for minimum TRISCAN errors, would be at the antenna location. At other locations, factors such as ship flexing could give rise to discrepancies between the measured roll and pitch (at the transducer location) and the actual roll and pitch at the landing pad. However, at locations other than at the ship's roll and pitch axis, the transducers are subject to cross axis accelerations that may degrade accuracy. Consequently, although the published transducer specifications indicate that the basic devices meet the ±0.02° accuracy goals, the cross axis sensitivity (0.3°/g) must also be considered in defining the area on board ships in which the transducer must be located to achieve overall system accuracy objectives.

Yaw stabilization data is readily available on all Navy ships[1] to varying levels of accuracy (0.05 to 0.25°) dependent on the specific gyrocompass model on board. The short term stability (perhaps 5 to 10 seconds) is a requisite to avoid perturbations of the guidance path seen by the approaching aircraft; especially when the aircraft is close.

The purpose of this task was to investigate and search out techniques, systems and devices that could measure ship's motion as needed by the landing guidance system. For roll and pitch data, this goal has been successfully achieved by identifying a potential supplier.

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1 As noted earlier, provided gyro repeater capacity is not exceeded.

However, several questions remain that can only be answered by actual testing, not within the scope of this program, of the hardware under simulated conditions. First, test verification of the published data must be made, under static and dynamic conditions. This will determine whether there are, and their significance, velocity lag effects. Then performance under simulated (and complex combinations of roll, pitch and heave) ship's motions must be evaluated to determine if the device is capable of operating satisfactorily as intended.

5.2.2 LINEAR MOTION SENSORS

No simple transducer can directly measure displacement without a fixed reference point, obviously not possible on board ship. The "straight forward" method to determine linear displacement is to measure the acceleration and perform a double integration. To avoid measurement errors caused by accelerations due to roll and pitch, the accelerometer's sensitive axis must be stabilized against rotational motions.

For heave, the sensitivity axis must be kept vertical; and this necessitates the use of a stabilized platform. In fact, several "Heave Sensors" are currently marketed and they all make use of a reference platform to keep the accelerometer aligned to perform the desired measurement. These units are relatively expensive costing over $10,000., and are generally used for measuring ocean wave height. Consequently, their design has features (such as 65 feet maximum range) well beyond that needed to measure ships heave adequately for TRISCAN requirements.

There are no known devices specifically tailored to measure sway and surge on a ship that is pitching and rolling. Some devices, called "Sway and Surge" sensors measure linear motions with respect to their baseplate. They are essentially accelerometers configured in a double integration system. So, a stabilized platform is needed to obtain sway and surge parameters without the angular motion induced errors.

To sum up, no specific off-the-shelf device is presently available that meets the requirements for a linear motion sensor that can measure heave, surge and sway. The problem can be divided into two areas--first a linear motion measuring system; and secondly a stabilized platform--the design of each is well within the state of the technology.[1] As noted above, heave, surge and sway sensors measuring motions relative to their monitoring base are commercially available, and pertinent specifications of one are:

Heave	
Range	± 40 feet
Accuracy	1% of range
Resolution, Threshold and Repeatability	0.5% of range
Frequency Response	0.03 Hz to 20 Hz
Surge and Sway	
Range	± 35 feet
Accuracy	1% of range
Resolution, Threshold and Repeatability	0.5% of range
Frequency Response	0.03 Hz to 20 Hz

The design of stabilized platforms is also well known, its significant drawback being cost.

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[1] AD 752453, Report 3260, "Design of Stable Integration Systems for Motion Measurement" by J. D. Gordon, NSR&DC, Bethesda, Md., August 1972. Gives a method of designing integration systems to obtain absolute ship motion by integrating accelerometer outputs.

Regardless, further study and "onboard observations" continuing the work done by NSRDC[1] is needed to precisely define the operational parameters associated with heave, surge and sway stabilization. The results of such a study would be the quantitative specification for the linear motion sensor (which, in the end, may not include one or all of these parameters), and permit the start of a design to provide the most cost effective hardware to meet the TRISCAN guidance requirements.

5.3 DATA LINK

A data link is needed to transmit stabilization related data and other auxiliary (not defined at this point) information to the approaching aircraft. Although the JTIDS (Joint Tactical Information Distribution System) presently under development eventually will provide the data link channel for the operational system, it is unlikely to be readily available for use during the early stages of TRISCAN testing and deployment. Therefore, an interim data link, as an integral part of TRISCAN, transmitting during the guard times between angle data transmissions and sharing one of the Ku-Band transmitters will be described later in this section.

Although the total data required by the aircraft is not specifically defined at this time, it tentatively can be classified into two areas--dynamic and static. Dynamic data includes roll, pitch, yaw, heave, surge, sway, deck level status--all of which continually influence, more or less, the approach flight path and the landing maneuver. Static data is usually auxiliary data needed periodically for general information purposes. Possible examples of static data are station identification, baseline lengths between stations, approach quadrant, etc. In the final analysis, perhaps the majority of the above identified data may not be needed, and therefore, not transmitted.

[1] Ibid; SPD-525-01

The data rate and capacity of the link rate accommodate the signals in timely manner to assure satisfactory operation during all phases of the landing operation. There should be no degradation of system accuracy, due to either errors or resolution limitations in the data transmitted or due to the staleness of the data, e.g., the information content is wrong by the time the aircraft receives it. Presently assumed requirements are shown in Table 5.1. The minimum resolution has been selected on the basis of not degrading basic system accuracy of 0.1°. Nine binary bits plus sign bit are assigned for the numerical values in the data link format. Therefore, either larger maximum values can be used with the listed resolution; or the resolution can be reduced, keeping the same listed maximum values:

TABLE 5.1 DATA DESCRIPTION

DYNAMIC DATA	MAX VALUE	MAX RATE	RESOLUTION
Ships roll angle	19°	6°/sec	.0625
Ships pitch angle	7°	2°/sec	.0625
Ships yaw angle	1.5°	1°/sec	.0625
Ships heave	18'	6'/sec	.0625'
Ships surge	5'	2'/sec	.0625'
Ships sway	6'	3'/sec	.0625'
Deck Level Status (Go-No-Go)	1	0	1
Wave Off Alarm (Go-No-Go)	1	0	1
STATIC DATA			
Approach Quadrant (port-starboard)	1	0	1
Baseline Length	128'	0	0.25'
Glidepath Angle	30°	0	.0586

Conservative values are shown in the table. The intent is to show that the data link format and capacity detailed below will satisfy these extreme requirements and certainly be adequate for lesser rates and capacities.

Taking the worst case, that of transmitting a complete message per uplink cycle, requires a message of 83 data bits. Allowing additional bits for identification, synchronization, etc., a 100 bit word would be sufficient. Obviously, the static data and some of the dynamic data need not be transmitted on a regular basis, and consequently the word length can be substantially reduced.

5.3.1 JTIDS DATA LINK

JTIDS will be the common communications carrier for all suitably equipped elements; on a time multiplexed basis. As presently envisioned,[1] there will be a 12.8 minute Epoch divided into 64 12 second frames, further subdivided into 1536 time slots each 7.8125 ms long. The basic message capacity is 456 bits, of which about 225 bits is available for data with the remaining bits reserved for error checking, secure coding etc. Consequently, one time slot is more than adequate to transmit all pertinent guidance sensor data.

The basic rate is 128 time slots per second. If we assume about a 10 Hz update rate for dynamic data, then 10 time slots would have to be reserved for the guidance sensor data uplink. This represents 0.78% of the total communications system capacity. Whether or not this is a reasonable or an excessive utilization of the JTIDS capacity is very difficult for us to judge; it is outside the scope of our knowledge now (and present need to know). Naturally, reducing the update rate correspondingly reduces the TRISCAN loading on JTIDS. Obviously, the above discussion is quite tentative due to the many uncertainties and undefined variables of both the guidance sensor and JTIDS, but it does give an indication of communication channel loading requirements needed by the Guidance Sensor System.

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[1] Seek Bus, C. Eric Ellison, Mitre Corporation, paper presented at EASCON, 1974.

5.3.2 INTEGRAL DATA LINK

As noted earlier, JTIDS may not be available during the preliminary testing and evaluation of TRISCAN. Therefore, an integral data link transmitting during the guard times between angle data transmissions is described below. Note that fixed PRF transmissions are always present during the guard times for the one-way doppler range rate computations.

With 10 scans a second and a data link burst in each guard band, 30 data words may be transmitted each second. These bursts will be for approximately 1 millisecond and will be recognizable by a unique pulse pair spacing. The spacings will be 18 and 19 usec (angle data pulse pair spacings are less than 15 usec) and can be handled by the guidance recovery circuits of the ARA-63 receiver. An auxiliary data link decoder is necessary to process the data link data.

The data link transmission will be a series of 16 pulse pairs with a constant 60 usec interpair spacing. A fixed directional antenna covering the entire approach sector will transmit the data. The intrapulse pair spacings, either 18 usec or 19 usec corresponding to binary 0's and 1's respectively, represent the binary code. In each code burst, see Table 2, the 16 bit word consists of a 4 bit data identifier, 10 bits representing the parameter magnitude and sign, one bit associated with static data and one bit for a parity check. The 16 bit static word is recovered from 16 successive bursts.

The remaining parameters are considered less significant and accordingly are updated less often. This of course, is subject to modification as we learn more about the system on-board performance.

Table 5-2, an example of a data link format illustrates the transmission of roll angle, pitch angle and heave on every sixth data link burst. Because the nominal period of these ships motions are in the order of 6 to 10 seconds (1/10 to 1/6 Hz), an update rate of 5 Hz should be adequate. However, if the update rate is not enough for roll and/or pitch, the data link capacity can be doubled, for example, by going to a 25 bit word. Note that the

TABLE 5-2. EXAMPLE OF DATA LINK FORMAT

SUCCESSIVE BURST TRANSMISSIONS

P = Odd parity bit
S = Static data bit

IDENTITY ±	VALUE MAGNITUDE	S	P	IDENTITY	(Value)	DATA BURST
1 1 0 0 0	0 1 1 0 0 0 0 1 1	1	0	Roll	-12.1875°	1
1 1 0 1 1	0 0 0 0 1 1 1 1 1	0	0	Pitch	+ 1.9375°	2
1 1 1 0 1	0 0 0 1 1 0 1 0 0	0	0	Heave	+ 3.2500'	3
1 1 1 1 1	0 0 0 0 1 0 0 0 0	1	0	Level OK	+ 1	4
0 1 1 0 1	1 1 1 0 1 0 0 0 1	1	0	Spare	+29.0625	5
0 0 1 1 0	0 0 0 0 0 1 0 1 0	0	1	Spare	- 0.6250	6
1 1 0 0 0	0 1 0 1 1 0 1 0 0	1	0	Roll	-11.2500°	7
1 1 0 1 1	. . . .	0	.	Pitch	+ 2.3125°	8
1 1 1 0 1	. . . .	0	.	Heave	+ 3.4375'	9
1 1 1 1 1	0 0 0 0 1 0 0 0 0	1	0	Level OK	+ 1	10
0 1 1 0 1	. . . .	1	.	Spare	+16.0625	11
0 0 1 1 1	. . . .	0	.	Spare	+ 4.3750	12
1 1 0 0 0	. . . .	0	.	Roll	-10.1250°	13
1 1 0 1 1	. . . .	1	.	Pitch	+ 2.5000°	14
1 1 1 0 1	. . . .	1	.	Heave	+ 4.8750°	15
1 1 1 1 0	0 0 0 0 0 0 0 0 0	0	1	Level NG	- 0	16
0 1 1 0 1	0 0 1 0 0 1 1 0 1	1	1	Spare	+ 4.8125	17
0 0 1 1 .	. . . .	0	.	Spare		18
1 1 0 0 .	. . . .	0	.	Roll		19

± P)
(1 0 0 1 1 0 1 0 0 1 1 0 0 1 1 1)
(First 16 static-data bits after null set*)

Static data:
Baseline A +38.25'
Q = approach quadrant #1

*Static data null set is 14 zeroes bracketed by ones: 1000000000000001.

relative rates of changes of ships motion parameters indicates the need for interpolation between samples in order to maintain absolute accuracy of the guidance angle data. Spare transmissions would be applicable to the parameters that can be uplinked at reduced update rates.

The pulse transmissions for the data link are consistent with existing equipment capabilities. With an assumed azimuth transmission sector of 136° and an elevation transmission sector of 60°, the transmitter duty cycle is 0.0023. The addition due to the data link is about 0.00025. Therefore, the total duty cycle is 0.0026, the transmitter is capable of a minimum of 0.004. The 60 usec interpair spacing allows the same recovery time now imposed as a minimum; and finally, the 18 and 19 usec intrapair spacings avoid both the range of spacings used for guidance signal identification, and the echo delay spacings (less than about 8 usec) that might arise from multipath.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The objectives of this project were to determine:

A. Basic System Positioning Accuracy

B. Effects of RF Multipath

C. Range Rate Accuracy

A. Basic system angle accuracies was demonstrated to be satisfactory to achieve the ±1 foot target accuracy requirement at the landing pad. Measured range accuracies in the coverage zone were 33 feet at 600 feet range and at 800 feet range, it was 55 feet.

B. RF Multipath was generated under test conditions and the basic system linear positioning accuracy remained within the bounds as stated in A above.

C. Computed range rate was better than the target requirement of ±1 ft/sec within 300 feet of touchdown. Beyond this range, detailed analysis indicates that noise error components, if left uncompensated, exceeds the stated requirements. The measured range rate error was 3.14 fps in the 600-675 foot sector, while the crosstrack and height rate errors was under 0.5 fps.

In addition to the above three main areas of investigation, related tasks have been studied:

- Smaller antennas with direct drive
- Electronic stabilization techniques
- Required data link capacity

D. Accuracy achieved with smaller antennas has no significant difference from that achieved during the main tests with the larger antennas. Synchronization of these antennas at the higher speeds planned for TRISCAN was also demonstrated.

E. Methods of electronic stabilization required for TRISCAN angle compensation can be based upon existing sensing techniques.

F. The data link needs of the TRISCAN system can be met by either the integral Ku-Band data link, or JTIDS. If the Ku-Band system is used as an interim, it will be of a modular nature that can be deleted if or when JTIDS is available.

6.2 RECOMMENDATIONS

A. Study and investigate techniques (such as DME, accelerometers, Kalman filtering techniques) that will provide accurate range position - accurate angle data is available from TRISCAN - from 10 miles through TRISCAN transition.

B. Further studies and investigations to rigorously define motion sensing requirements, then breadboard and/or simulation verification of the ship motion sensing and compensation system prior to final design of an advance development model to ensure minimum risk of delay in that program.

APPENDIX

Related subjects critical to the understanding of TRISCAN performance and its application as the NAVTOLAND guidance sensor are discussed in this appendix. First, to complete the data relevant to the field test program, the antenna beam patterns of the actual antennas used in the CO-SCAN equipments in the field tests are shown in Appendix A. Secondly, the accuracies of the small antennas that would be used with the higher data rate system are tabulated and discussed in Appendix B. Finally, the Direct Drive Antenna Synchronization System, associated with higher data rate system, is described and its test performance shown in Appendix C.

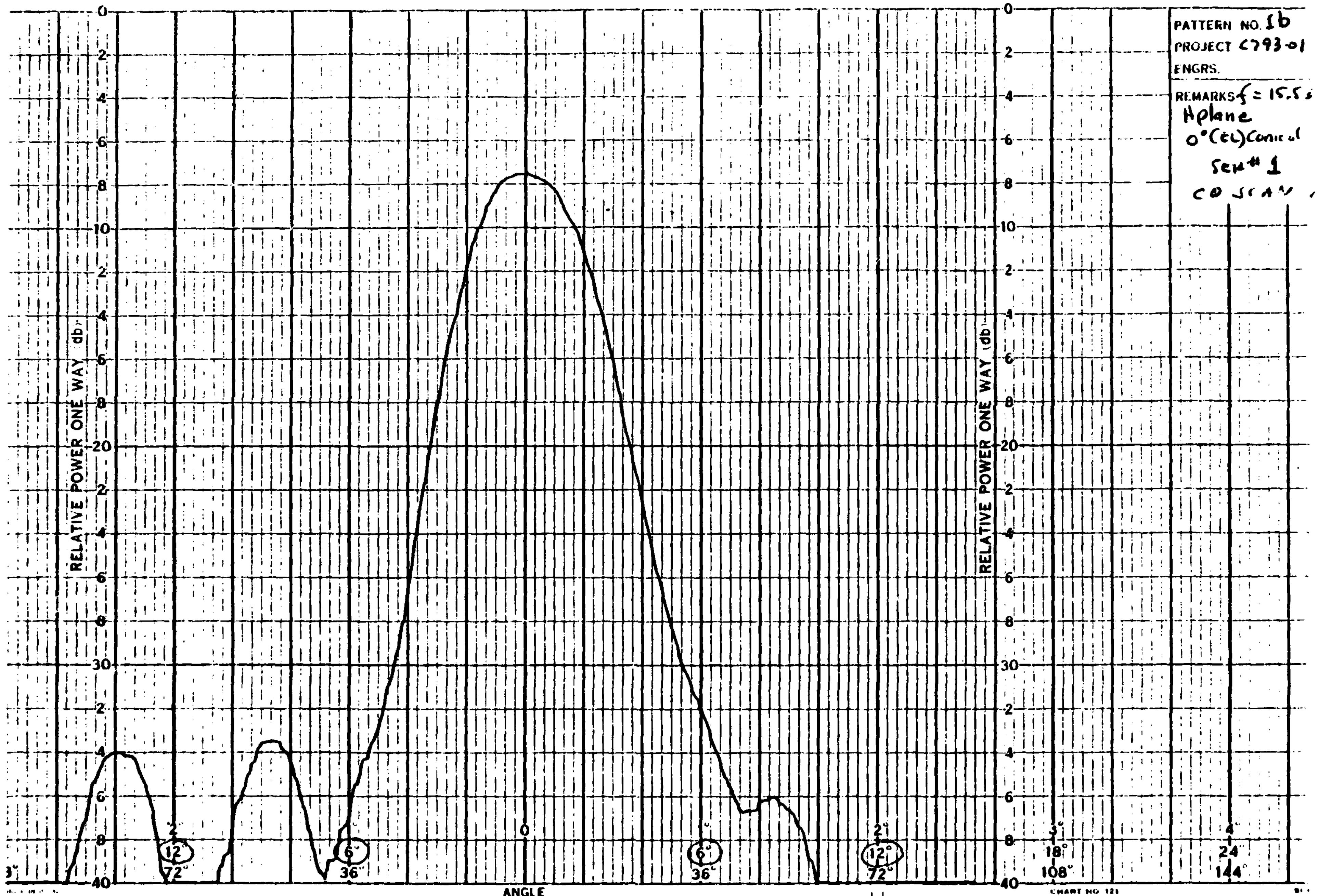

FIGURE A-1. AZIMUTH 1 ANTENNA PATTERN (H PLANE)

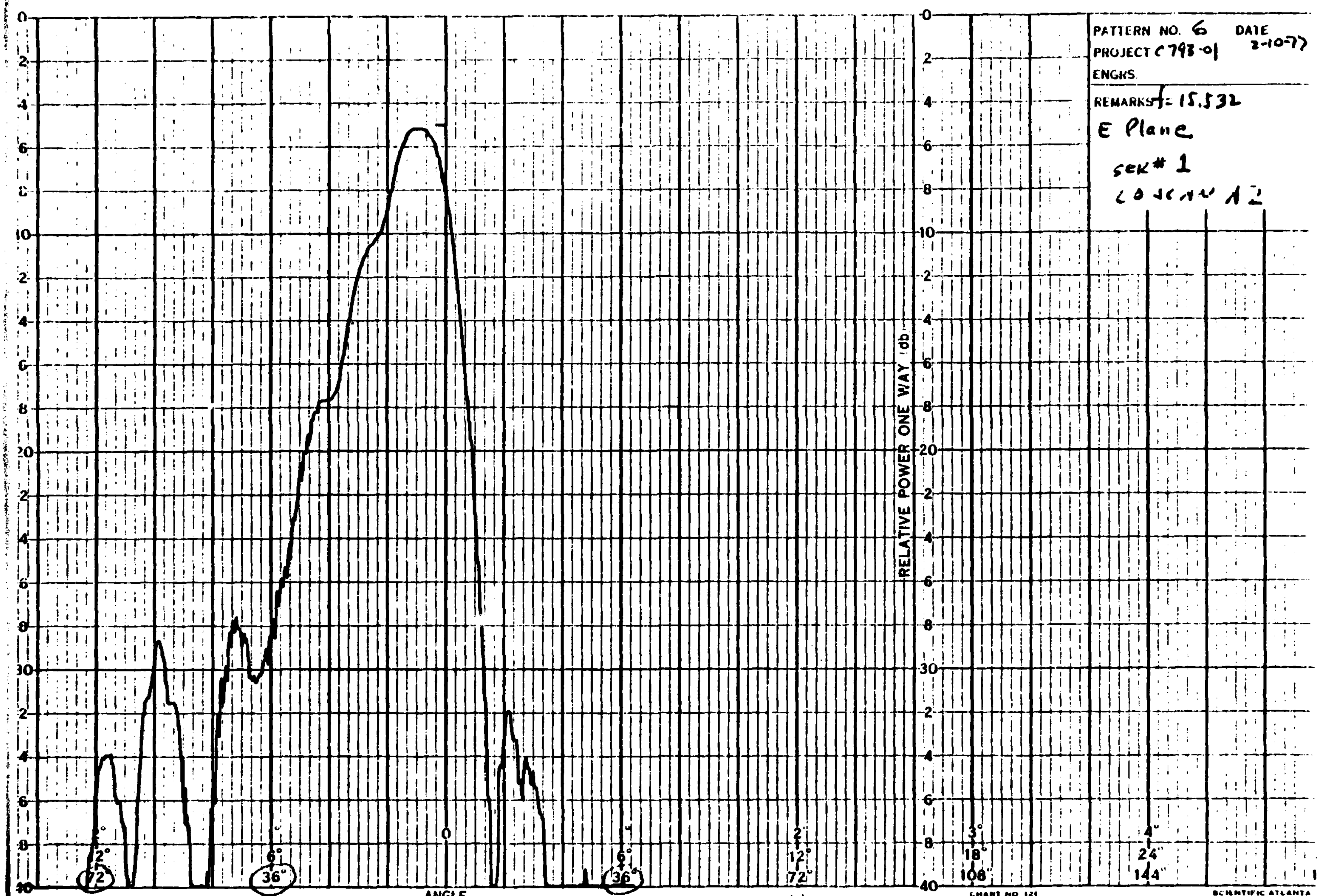

FIGURE A-2. AZIMUTH 1 ANTENNA PATTERN (E PLANE)

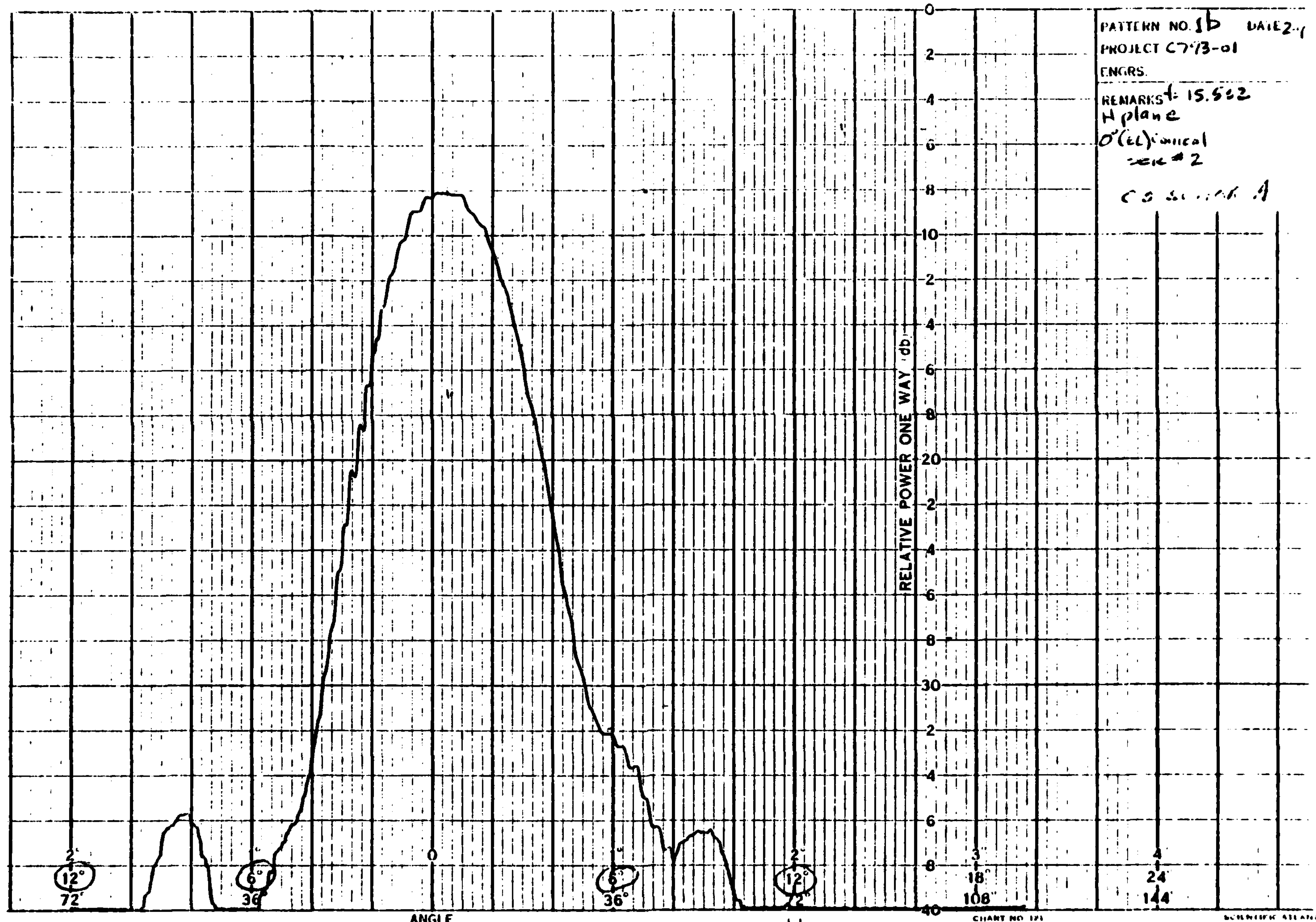

FIGURE A-3. AZIMUTH 2 ANTENNA PATTERN (H PLANE)

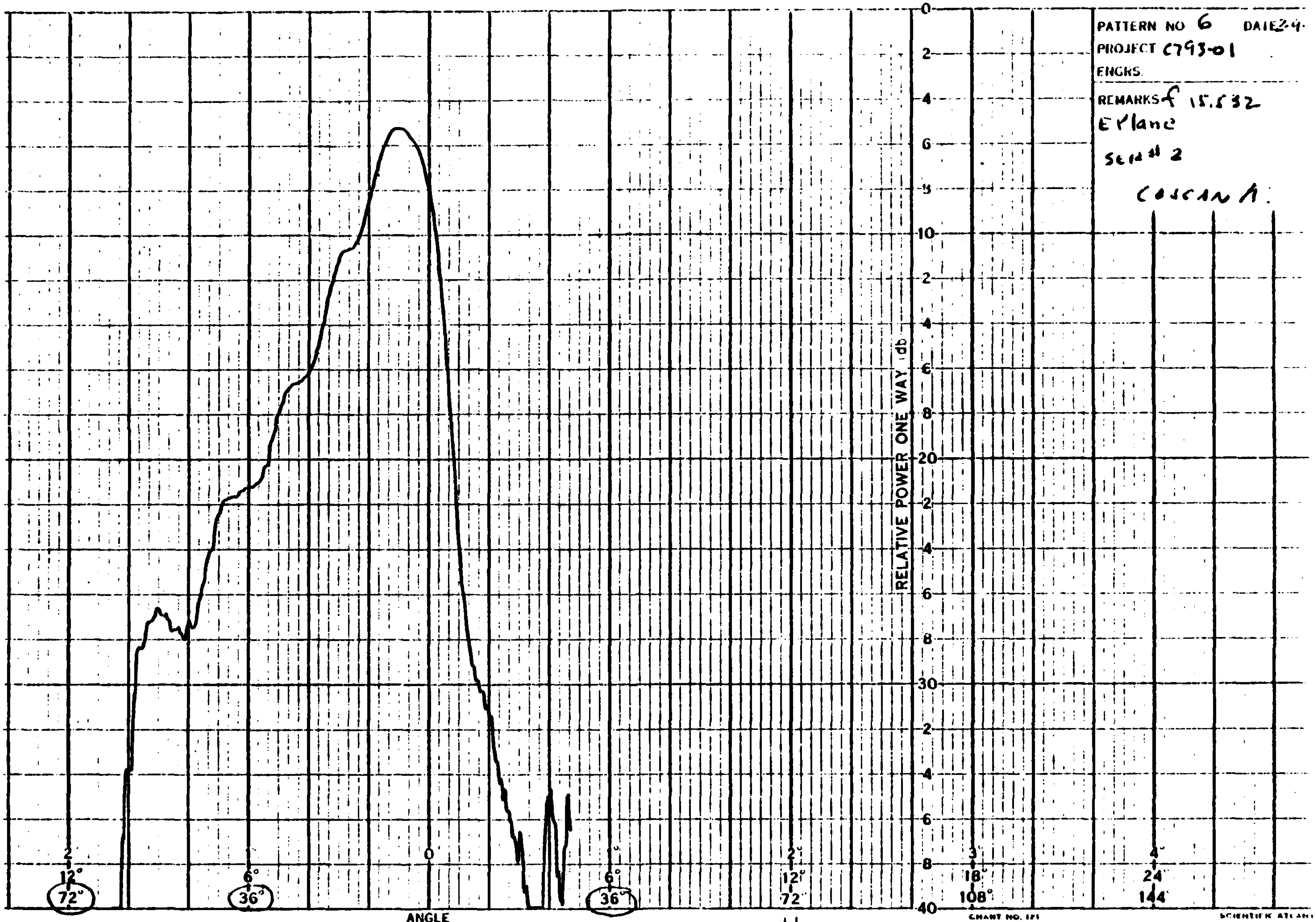

FIGURE A-4. AZIMUTH 2 ANTENNA PATTERN (E' PLANE)

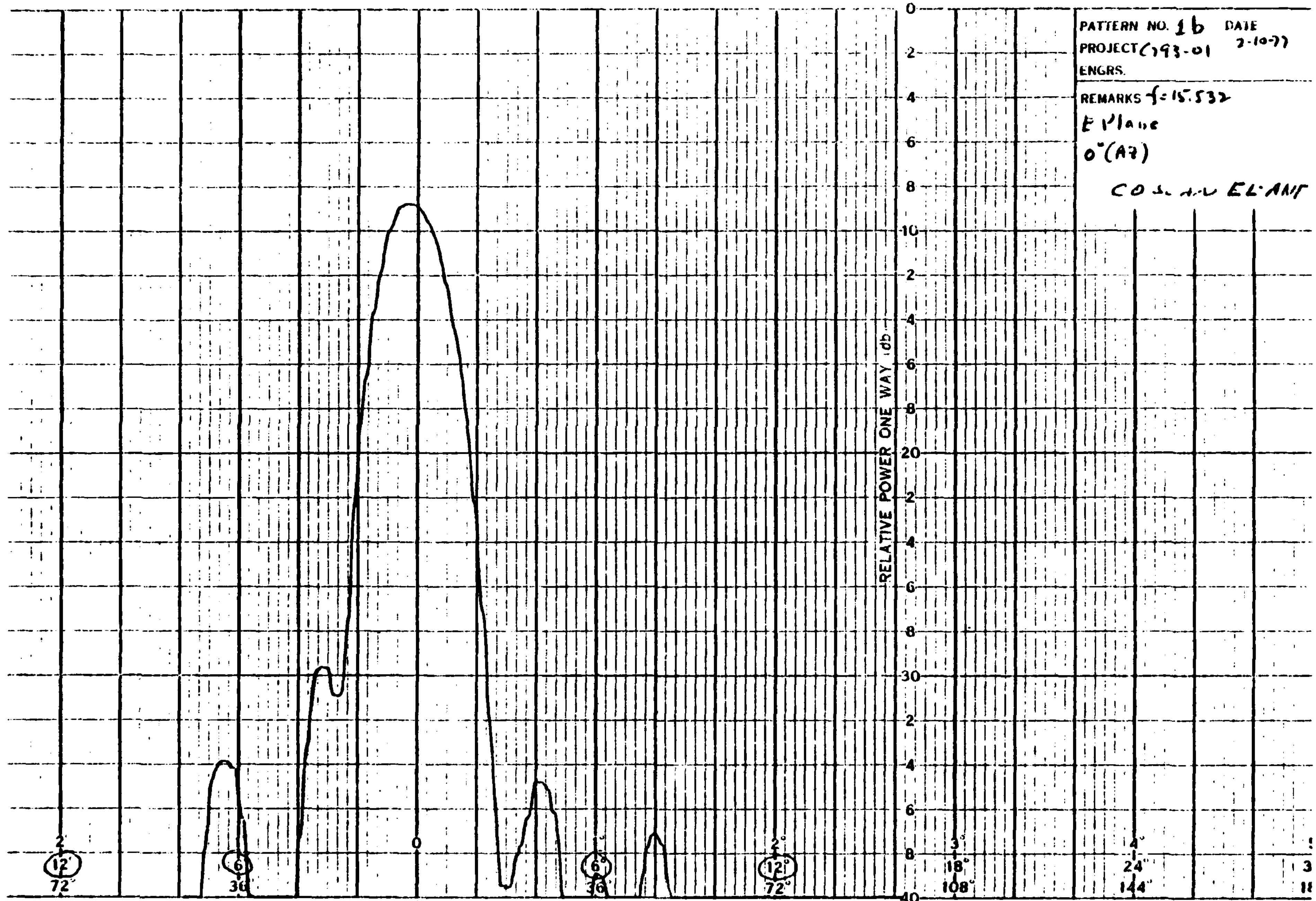

FIGURE A-5. ELEVATION ANTENNA PATTERN (E PLANE, 0° AZIMUTH)

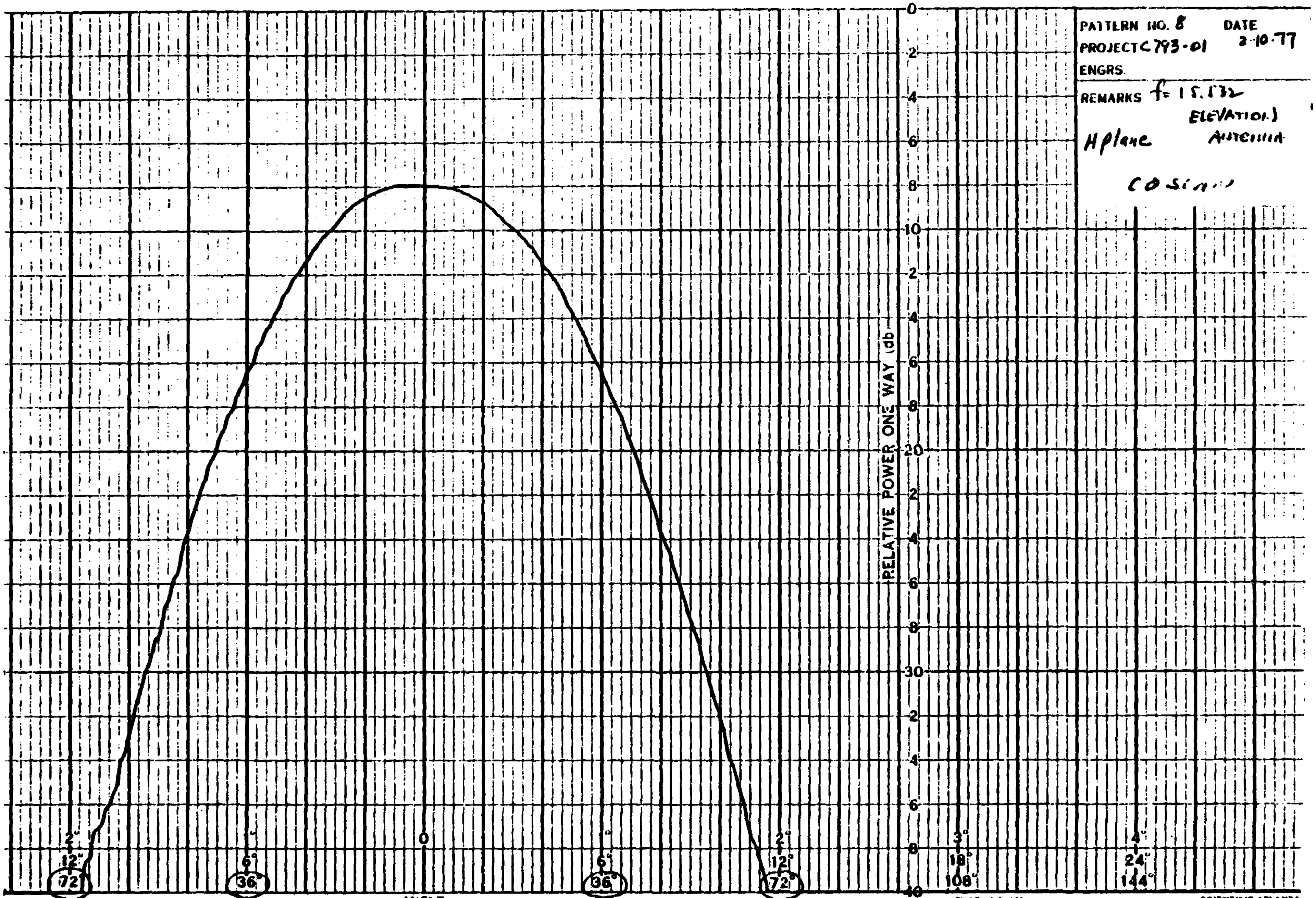

FIGURE A-6. ELEVATION ANTENNA PATTERN (H PLANE)

B. SMALL ANTENNA PERFORMANCE

Small antennas were installed in the standard COSCAN station and system accuracy was measured at several different azimuth angles and as a function of range. Due to the test range configuration, the COSCAN station itself was rotated appropriately to permit measurements at the different azimuth angles. Normally, the antennas would be aligned and boresited to remove bias errors. Because the purpose of these tests was to measure system accuracies, and it would have been necessary to reboresite each time the station was moved, no attempt was made to boresite the small antenna configuration. Boresite errors appear as a constant bias error independent of range and recognizeable as such does not affect the test results.

Table I summarizes the azimuth errors relative to the nominal azimuth angle at each azimuth. The mean bias (boresite) at each azimuth is shown and the corresponding actual error is the nominal error minus this mean. As can be seen, variation in system accuracy as a function of range is insignificant. Although data shows errors above 0.1° at 10 feet, this is negligible since it produces a maximum position error of less than 1/2 inch at this range. Similarly, Table II shows elevation performance as being unaffected as the receiver approaches the transmitter and is well within the near field of the small antenna.

To sum up, smaller aperture antennas with their corresponding broadening of beam width are quite suitable for use at higher data rates. There are no noticeable effects on system accuracy as a function of receiver range, even down to within 10 feet of the transmitting antenna.

TABLE B-1

SUMMARY OF STATISTICAL EVALUATION

OF AZIMUTH ANGLE DATA

RECEIVER POSITION		AZIMUTH ANGLE ERROR*			SIGMA			ACTUAL ERROR		
RANGE (ft)	HEIGHT (ft)	+9°	0°	-9°	+9°	0°	-9°	+9°	0°	-9°
10	1.7	.095	-.062	.330	086	055	044	.108	-.187	.091
10	3.3	.117	-.048	.246	064	043	040	.130	-.173	.007
20	1.7	-.015	.094	.299	047	030	040	-.002	-.031	.06
20	3.3	-.019	.040	.234	041	027	086	-.006	-.085	-.005
20	5	-.076	-.010	.194	059	041	043	-.063	-.135	-.045
40	1.7	.088	.163	.279	047	049	042	.101	.038	.040
40	3.3	.025	.131	.278	046	036	049	.038	.006	.039
40	5	-.033	.051	.188	049	034	044	.064	-.074	-.051
40	10	.145	.135	.285	046	030	045	.158	.01	.046
80	5	.002	.113	.220	051	036	043	.015	-.012	-.019
80	10	-.026	.112	.225	035	030	046	-.013	-.013	-.014
80	20	-.107	.102	.209	075	046	042	-.094	-.023	-.030
80	30	-.022	.114	.209	049	044	047	-.009	-.011	-.030
100	5	.013	.066	.217	065	038	043	.026	-.059	-.022
100	10	-.010	.155	.224	057	034	047	.003	.030	-.015
100	20	-.179	.152	.179	074	036	042	-.166	.027	-.06

TABLE B-1 (CONT'D.)

RECEIVER POSITION		NOMINAL AZIMUTH ANGLE ERROR*			SIGMA			ACTUAL ERROR		
RANGE (ft)	HEIGHT (ft)	+9°	0°	-9°	+9°	0°	-9°	+9°	0°	-9°
100	30	.029	.131	.278	048	045	042	.042	.006	.039
200	10	-.096	.181	.249	065	038	045	-.083	.056	.01
200	20	-.126	.144	.227	064	037	035	-.113	.019	-.012
200	30	.014	.134	.136	039	036	040	.027	.009	-.103
200	39	-.024	.094	.050	052	041	048	-.011	-.031	-.189
400	10	-.002	.261	.369	057	038	046	.011	.136	.130
400	20	.141	.123	.199	061	041	054	.154	-.002	-.04
400	30	.039	.240	.246	044	039	044	.052	.115	.007
400	39	-.097	.168	.270	064	038	047	-.084	.043	.031
600	10	-.024	.149	.260	056	040	041	-.011	.024	.021
600	20	-.018	.181	.299	054	035	052	-.005	.056	.060
600	30	-.013	.194	-	061	034	-	0	.069	-
600	39	-.084	.174	-	064	039	-	-.074	.049	-
900	10	-.006	.162	.233	057	039	049	.007	.037	-.006
900	20	-.052	.180	.279	070	042	059	-.039	.055	.040
900	30	-.058	.164	.267	060	039	041	-.0450	.039	.028
900	39	-.058	.148	.229	059	042	049	-.0450	.023	-.010
	MEAN	-.013	.125	.239						
	SIGMA	.074	.071	.059						

* NOMINAL MEAN - (9, 0 or -9)

TABLE B-2

SUMMARY OF STATISTICAL EVALUATION

OF ELEVATION ANGLE DATA

RECEIVER POSITION			NOMINAL ELEVATION ANGLE ERROR*			SIGMA			ACTUAL ERROR		
RANGE (ft)	HEIGHT (ft)	APPROXIMATE ANGLE (DEG)	+9°	0°	-9°	+9°	0°	-9°	+9°	0°	-9°
10	1.7	10.0	.851	.822	.743	.052	.071	.048	-.047	.047	.001
20	3.4	9.8	.928	.838	.805	.054	.045	.054	.030	.063	.063
40	5	7.3	.926	.698	.688	.066	.036	.041	.028	-.077	-.054
80	10	7.2	.914	.740	.696	.060	.029	.058	.016	-.035	-.046
80	20	14.1	.973	.716	.800	.068	.058	.059	.075	-.059	.058
100	10	5.8	.999	.870	.675	.056	.050	.042	.101	.095	-.067
100	20	11.4	.780	.703	.784	.040	.066	.036	-.118	-.072	.042
200	20	5.7	.951	.745	.645	.030	.047	.032	.053	-.030	-.097
200	30	8.6	.955	.839	.841	.053	.076	.069	.057	.064	.099
200	39	11.1	.699	.780	.745	.067	.041	.058	-.199	.005	.003
		MEAN	.898	.775	.742						
		SIGMA	.094	.063	.065						

* MEAN - COMPUTED NOMINAL ERROR

C. ANTENNA SYNCHRONIZATION

TRISCAN requires the precise synchronization of three rotating antennas, two azimuth and one elevation. The antennas, in turn, transmit azimuth and elevation guidance respectively to approaching aircraft. The fan shaped beams, as they scan through the approach sector, are alternately intercepted by the approaching aircraft. Antenna coverage sectors have not been finalized and are subject to continuing analysis as considerations of different approach courses are being studied. Preliminary design was on the basis that total time for one complete transmission cycle in Azimuth 1, Azimuth 2, and Elevation, is 125 milliseconds. The three antennas are electronically locked so as one antenna radiates, the other two are scanned through their inactive portions of their rotation. Regardless of the specific configuration, about a 3.5 millisecond guard time (no angle data transmission) will be allocated to allow uplink transmission of angle related data, e.g., ship roll, pitch, etc. In addition, during this time, time has to be budgeted for RF switch on/off transitions as well as for synchronization jitter between the three antenna drive systems. Presently, an RF switch used in related programs is specified to switch in 1 millisecond maximum. Although the Data Link requirements are not firm, it is certainly desirable, at this time, to have the maximum possible time available as a design goal if an integral data link is needed. Toward this end, 1 millisecond has been selected as the objective for the synchronization band between antenna drives. Consequently, about 1 millisecond is left for the data link transmission. As discussed earlier, this time period is adequate.

SYNCHRONIZER SYSTEM

A direct drive system using a readily available commercial synchronous motor in an electronic synchronization loop was designed and successfully tested over the applicable temperature range. The system shown in Figure C.1 is essentially a phaselock design, and consists of a synchronizer module, digital to analog converter, power amplifier, synchronous motor and antenna geared one-to-one to a shaft encoder.

The test generator, simulating the reference antenna drive, consisted of a variable speed synchronous motor drive geared to an ADP rotating at 8 RPS. The variable speed feature allowed performance to be measured above and below the nominal design speeds.

The Antenna Synchronizer is a phaselock system that can lock the azimuth to the elevation drive or vice versa. Both possibilities using either as a master and the other as the slave, were breadboarded and tested. Angle data pickoffs (ADP), geared one-to-one to the antenna, provide the Reference Gate (REG) and angle increment pulses (AIP) from the master antenna drive and the follow-up gate (FUA) when mounted on the slave. The feasibility breadboard reference ADP generated 256 pulses per revolution, or at 8 RPS, a pulse every 0.49 ms.

The synchronization is obtained by setting the frequency of the follow-up motor to that value which causes the follow-up (FUA) to occur a preset number of AIP's after the reference gate (REG). The reference ADP outputs, REG and AIP, feed counter A via the synchronizer control. REG enables the counter which starts its count from a preset number N. This number is a direct function of the desired phase lag between the follow-up and the reference. The counter counts AIP pulses until the FUA is detected. At this point, the accumulated count is transferred to the storage register which controls the rate multiplier scaling factor.

The rate multiplier output feeds a D/A sine wave converter whose output is amplified to drive the synchronous motor. The sine wave frequency is directly dependent on the rate multiplier output. When proper phaselock is achieved, the frequency remains constant with the number of counts between REG and FUA staying the same.

If FUA is late, the accumulated count is larger than nominal, thereby providing a higher multiplier factor, increasing the drive frequency and subsequently motor speed. This action accelerates the appearance of FUA decreasing the accumulated count in subsequent periods. This continues until an equilibrium is established. That is, the accumulated count is just adequate to provide the correct rate multiplier scale factor to maintain the steady state displacement between the REG and FUA.

Correspondingly, if the FUA is too early, the count is smaller than nominal and the subsequent drive frequency is decreased slowing down the motor and causing the FUA to lag until the equilibrium is reached.

Environmental tests were made on both azimuth and elevation as the slaves with a steady state speed of 8.4 RPS (119.5 ms period). The summary of test data is shown below.

TEMP.	ELEVATION TIME VARIATION FROM ROOM	AZIMUTH TIME VARIATION FROM ROOM
+50°	0	0
Room (+18°C)	-	-
-30°C	0	0.5 ms

As noted earlier, the design goal was to achieve a synchronization band of less than 1.0 millisecond which has been reached. The Angle Data Pickoff's low temperature specification is -30°C and, accordingly, synchronizer system low temperature tests were made at this temperature.

The objective of this task was to investigate and determine the feasibility of synchronizing the antenna systems electronically within the tight tolerances discussed above. This has been successfully accomplished. Although these results were not at a 10 Hz data update rate, they are applicable since the test speeds and the required speeds are comparable.

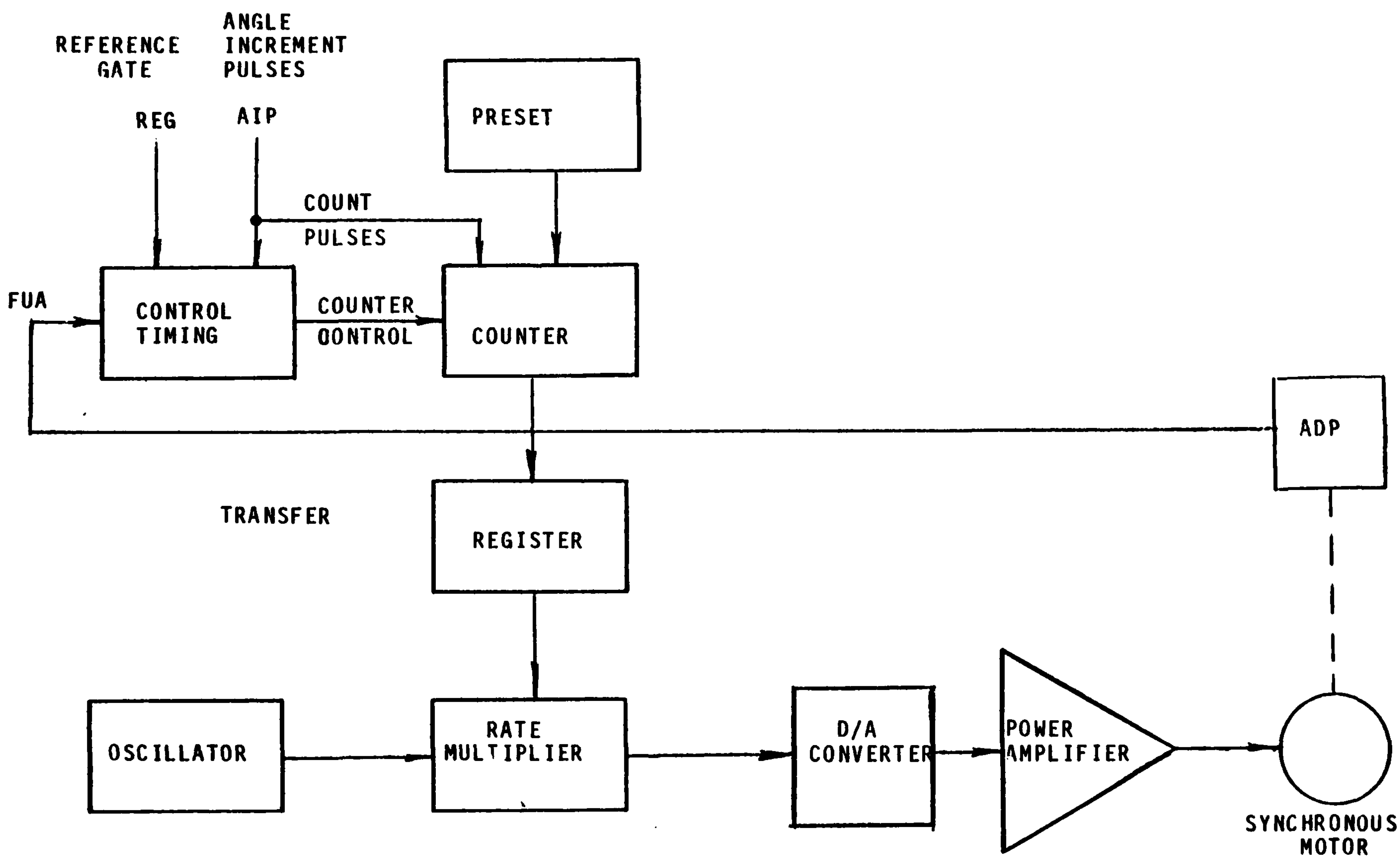

FIGURE C-1. ANTENNA DRIVE SYNCHRONIZER SYSTEM


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